TR-936

RELIABILITY AND COMPLETE ENVIRONMENTAL TESTING

Dr. E. W. Chittenden

5 June 1961

DIAMOND ORDNANCE FUZE LABORATORIES
ORDNANCE CORPS DEPARTMENT OF THE ARMY
WASHINGTON 25, D. C.

ORDNANCE CORPS

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DA-506-01-001
OMS 5210.11.111
DOFL Proj 20124

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ABSTRACT

The designer of a new and complex instrument for use in missiles is unable to predict the probable percentages of successful operation from tests because of the small number of models available. Analysis of the physical basis for high reliability suggests that confidence in an instrument can be obtained by a method of complete environmental testing that is formulated mathematically herein. This method has been applied to the testing of a family of high quality amplifiers in an environmental chamber permitting continuous and simultaneous variation of temperature, atmospheric pressure, and vibration, with the result that the designers obtained greatly increased confidence in the survival capability of the instrument.

1. INTRODUCTION

This report is an outgrowth of an analysis of a problem faced by engineers engaged in the design of components for guided missiles (ref 1 and 2). In advance of actual use, and in addition to the usual laboratory tests, the engineer desires methods of testing that apply to a completed instrument, use small samples, and give such substantial evidence of the ability of the instrument to endure the missile environment that he can confidently state that the instrument is ready for field trials. An examination of the factors that provide confidence in a design before field trials shows clearly that testing in simulated environments is of major importance (ref 3 and 4). An approach is proposed to the environmental problem that has not been followed systemically in engineering practice. The reasons for this will become apparent.

Consider, for example, the environment of a missile. For simplicity, the discussion will be limited to five factors: temperature, acceleration, vibration, ambient pressure, and time. Thus the environment to be considered is five dimensional. All these factors combine in some way during a flight. Since each missile type is planned for a definite flight, the intervals of variation of these factors can be calculated in terms of the range, altitude, and time. The product space of the ranges of the five factors is the environmental space of the missile. Of course, if more factors (for example, currents, charges, ionization, etc.) are considered, the number of dimensions can be larger.

In a flight of duration t, the center of gravity of a missile travels a path in real space of three dimensions. At each point of the flight there is a time, t, and an environment, E_t, with the factors temperature, external pressure, internal pressure, acceleration, vibration, and possibly shock. Assume that there are k of these factors and that their observed or calculated amounts are represented by $u_i (i = 1,2,\ldots,k)$. Thus at each time t, a point u(t) of a k-dimensional environmental space is determined and the flight determines a path in the space. The u_i are the coordinates of u(t).

In simulating a flight it is sufficient to determine the parts of the environment that the flight enters and test for these. If the environmental space is divided into sufficiently small rectangular cells, such a flight selects a chain of cells. We may consider that the flight represents this chain of cells. Conversely, the chain of cells may be so chosen that it will include all the cells entered by an entire family of flights. Considering that an actual flight represents a chain of environmental cells, the question naturally arises of whether we can estimate the effect of a flight that strays into other than the planned environmental regions. Thus overacceleration, overvibration, velocity beyond planning, high nose-cone pressures and temperatures may arise in various combinations.

This example illustrates the necessity for an adequate estimate of the multidimensional space in which the instrument is expected to operate. This space will be called the design space. Since the instrument may be operable in a larger environment than is required, we speak of the living space. The relation of the design space to the living space introduces a concept analogous to the factor of safety. A comparison of the design space with the living space of an instrument will provide information regarding its reliability (fig. 1, 2, 3).* That is, if the design space approaches the limits of the living space, we expect a less reliable instrument than would be the case if the design space were well within the living space.

The following methods and principles are employed in the design of an environmental test. It is convenient to consider only rectangular spaces. For present purposes, a neighborhood of a point of an n-dimensional environment is a rectangular solid with the point as center. In the design of a test, the range of each environmental factor is chosen to include the design requirements and lie within the capabilities of the components. This range is divided into steps such that the output of the instrument to be tested over a step can be fairly represented by an observation at one of its values. Because environmental changes occur in time, it is convenient and desirable to consider an environmental space as determined by n factors, excluding time. The special role of time in environmental analysis is clearly illustrated by the custom of speaking of changing environments. Thus, environmental factors are usually considered as functions of a common parameter, time. A factor that remains constant is a time invariant. When the test space has been partitioned into cells, the most convenient way to examine an instrument over the space is to pass a path through each cell (fig. 4). Uniform behavior over the entire test leads to a presumption that the output over this curve is representative of the output over the whole space. The hypothesis that at any point of the environment a moderate change in the coordinates leads to a small change in observed output is essential to the conclusion that the path is truly representative. Physical theory can

* For simplicity, two dimensional illustrations are given.

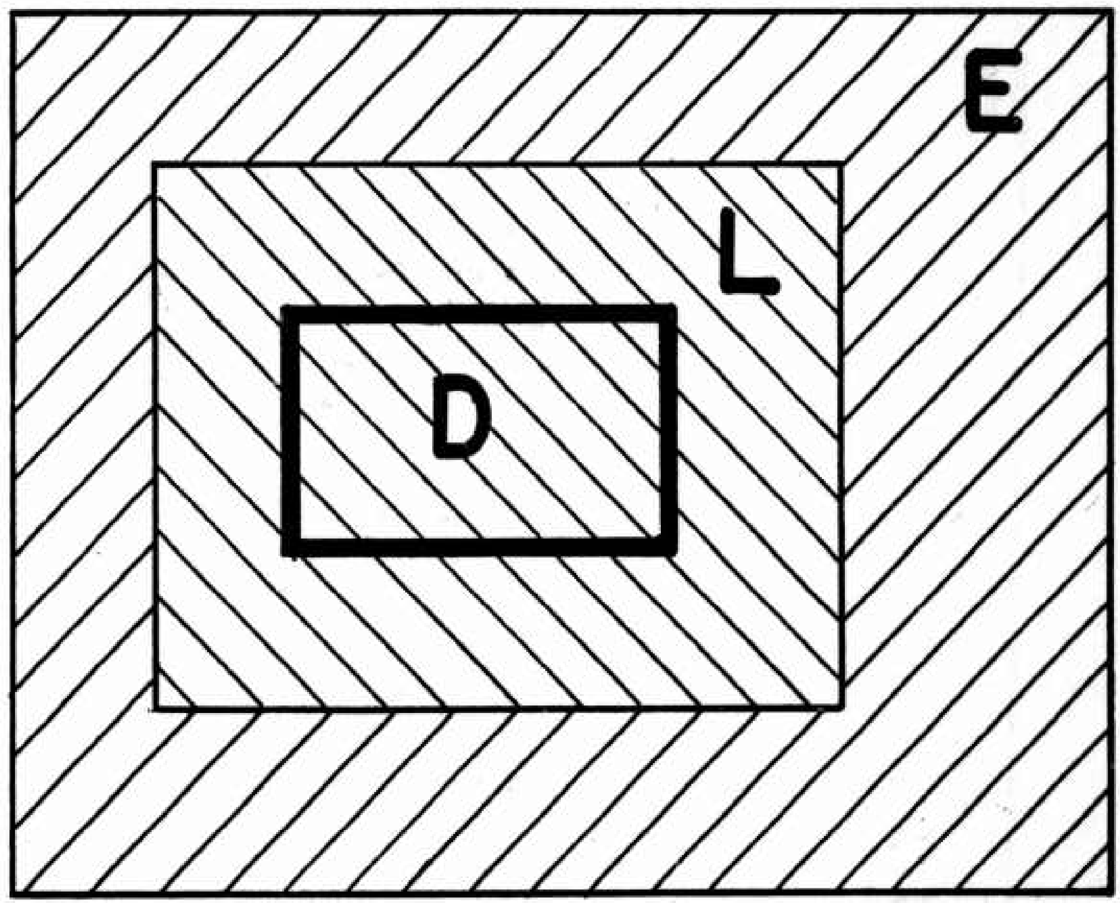

Figure 1. Favorable relation between design space D and living space L (D well within L).

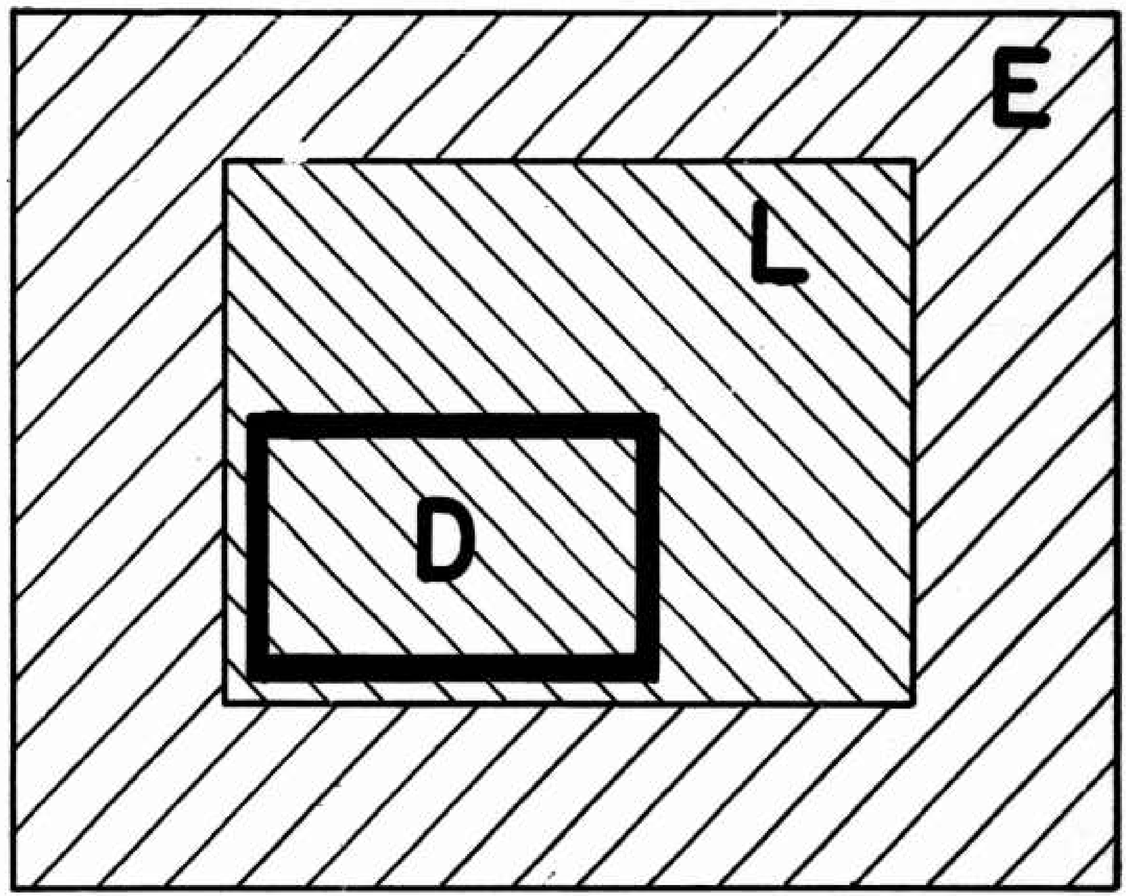

Figure 2. Intermediate relation between design space D and living space L. (D near boundary of L).

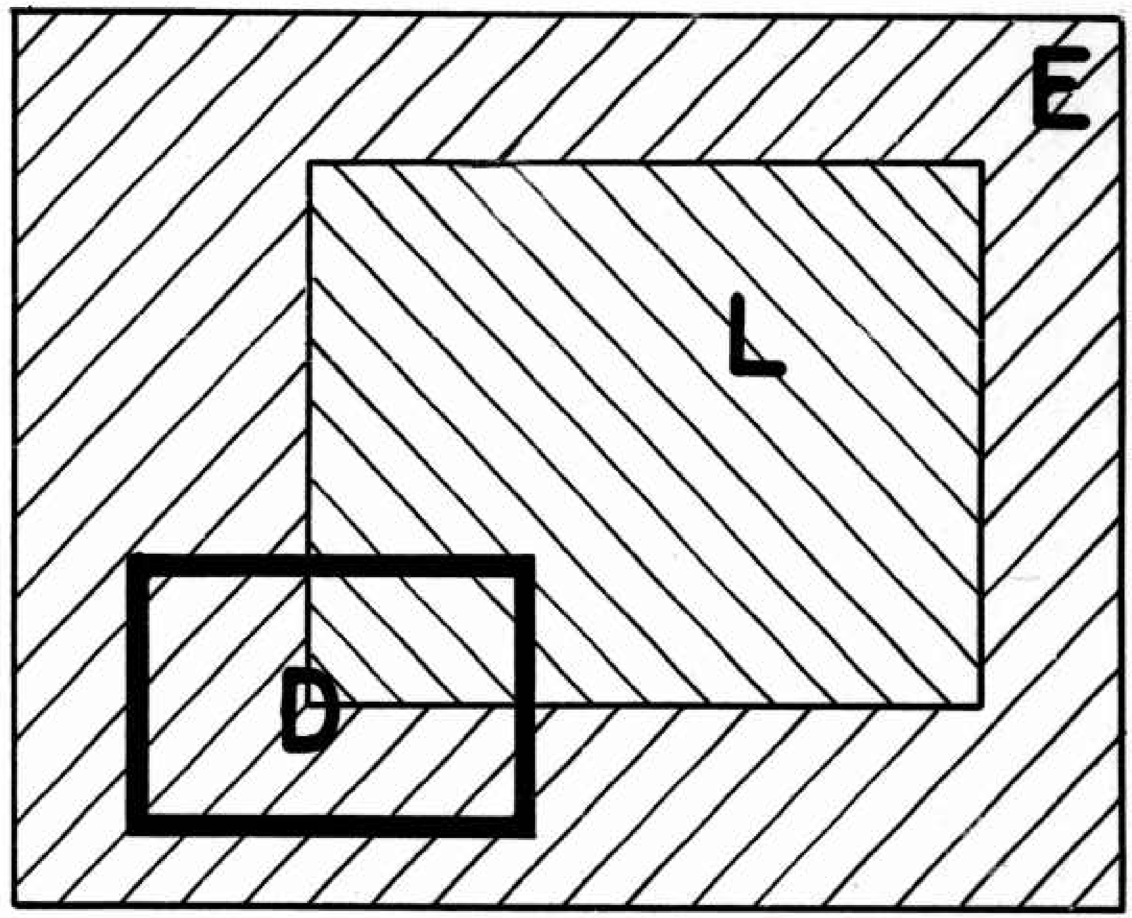

Figure 3. Unsatisfactory relation between design space D and living space L. (D intersects failure region E - L).

contribute to this conclusion. Generally speaking, the finer the system of divisions, the closer will be the correspondence between output along the path and output over the entire space. When all factors of an environment are fixed except one, and that one is varied, we speak of probing or linear testing. Figure 4 illustrates the difference between linear and f4
multidimensional testing.

The method of testing a whole environment discussed here will be called complete environmental testing. That is, the attempt is made to cover a whole region rather than a small part. Since the intervals of variation that bound a cell occur repeatedly as the path winds through the environment, any trouble spot must result from something special in the combination.

If an instrument fails to show a significant variation in output in an incomplete test of an environmental neighborhood, there is no proof that a failure point does not exist in that region. However, if the variations in output over a neighborhood are small, continuity of output throughout the neighborhood is expected.

Information regarding the extstence of critical points may be obtained in a variety of ways in addition to direct observation during a test. Knowledge of the properties of an instrument, in particular, its natural frequency, combined with the level of acceleration and the duration of exposure to a critical frequency, is an essential factor in environmental testing. Formulas regarding the relation of output to environmental changes covering the neighborhood of interest may show where singularities can be expected.

The method of testing outlined above is treated by formal mathematical methods in section 2. While these methods are elementary and well known to mathematicians, they are detailed and their application to the design of experiments is precise. For a body in motion, coordinates of position give rise to variations in environment. Thus the environmental coordinates are functions of position coordinates and time.

This study emphasizes the importance of an approach to the concept of reliability that is broader than but includes the current definition of reliability as a probability. An abstract theory of reliability in these terms has been developed (ref 1) that is suggestive of practical applications, including the one discussed in sections 3 and 4 of the present report.

While complete environmental testing is not designed for statistical purposes, it does provide opportunities to apply factor analysis to the question of which element or elements of an environment are responsible for observed variations in the output of an instrument.

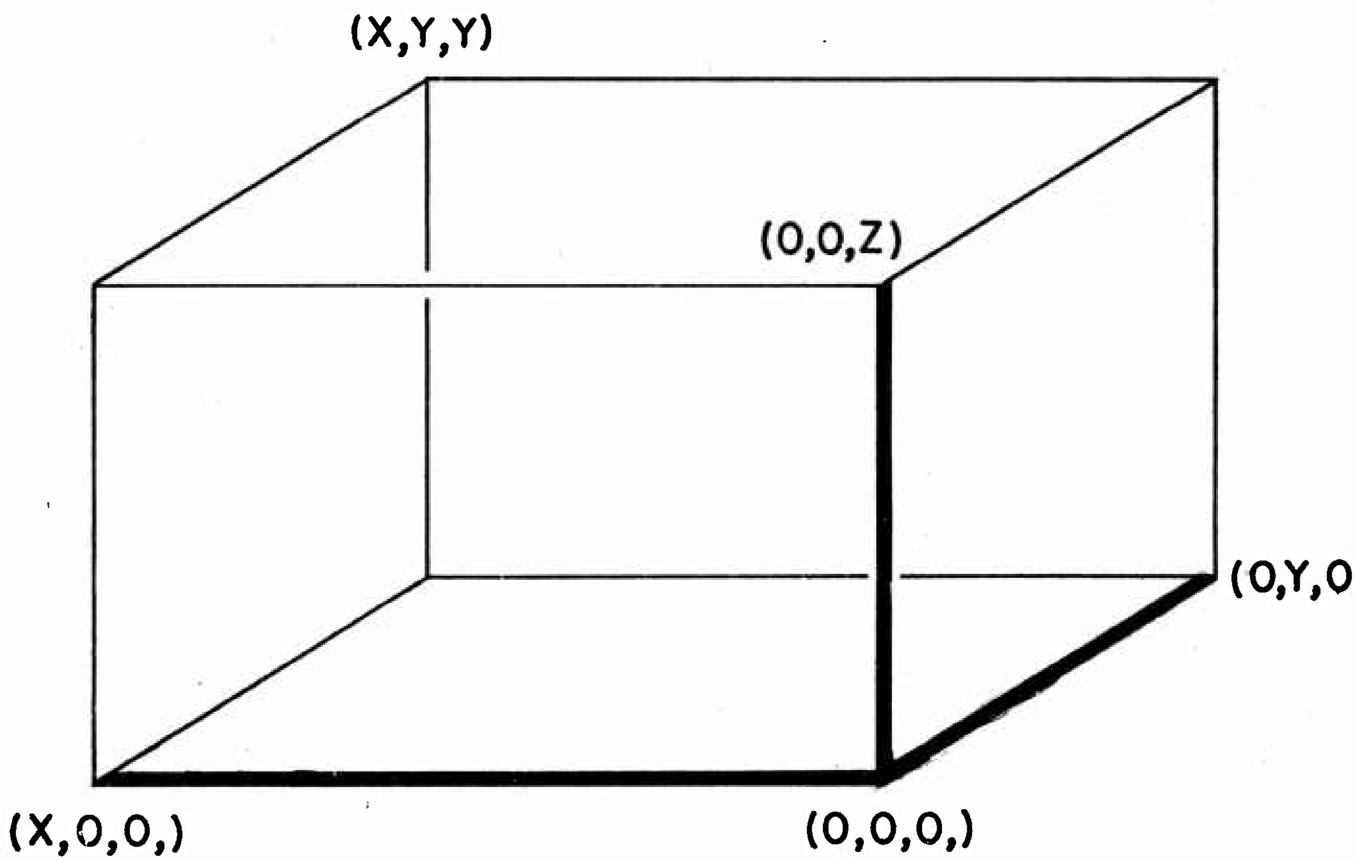

Figure 4. Comparison of linear and three-dimensional testing.

The disadvantage of complete environmental simulation is that the equipment required is elaborate. Without automatic controls, the operation outlined above requires several skilled operators and close attention throughout the duration of a test. Expert supervision for planning and direction is also necessary. The justification for this type of testing is found in the fact that it applies to important instruments and provides, in case the test is passed, a higher degree of confidence than is usually obtainable from linear probing.

At DOFL a family of high-gain amplifiers was developed for use as test vehicles. A preliminary report on the tests and the underlying mathematics are given in reference 2. Section 2 of the present report contains a discussion of various mathematical phases of the method of complete environmental testing. Section 3 presents the program and results of a first series of tests of an IF amplifier. Section 4 is concerned with a second series of amplifier tests. Appendix A contains an analysis of the amplifier design and the previously known qualities of its parts that provided an estimate of the living space used as a basis for the tests. Appendix B describes the equipment used in the tests.

2. MATHEMATICAL TECHNIQUES FOR COMPLETE ENVIRONMENTAL TESTING

2.1 Environmental Space

Let $u = (u_1, u_2, \ldots, u_k)$ be a set of real arithmetical values of k distinct parameters $u_1, u_2, \ldots, u_k$, which influence the operation of an instrument. For convenience u will be called a point; a collection of points will be called an environmental space and denoted by E. The spaces of the following discussion are rectangular Euclidean and the values of the parameters u_i are coordinates. The bounds a_i, b_i of a parameter u_i, finite or infinite, determine an interval of variation:

$$a_i \leqq u_i \leqq b_i \quad (i = 1,2,3,\ldots k). \tag{1}$$

The space E is k dimensional. It may or may not contain all the points u whose coordinates satisfy inequalities (1). It is usually convenient to assume that all possible values of the parameters satisfying inequalities (1) are represented. The limitations on the parameters u_i are imposed by physical conditions. For example, atmospheric pressure is never negative; temperatures cannot fall below absolute zero. While time is a parameter of great importance, we shall assume that it is not one of the u_i parameters and thus if for each value of i $(i = 1,2,\ldots,k)$, u_i is a function of time, the point u_i will lie on a one-dimensional path in the space E.

The following example of a three-dimensional environmental space is applied in tests discussed in section 3. Let u_1 (temperature), u_2 (frequency), u_3 (pressure) be given the bounds:

$$-70^\circ F \leqq u_1 \leqq 200^\circ F$$

$$50 \leqq u_2 \leqq 2000 \text{ cps}$$

$$0.164 \leqq u_3 \leqq 15 \text{ psi}$$

2.2 Living Space - Design Space

Let x denote an instrument and E an environment of x. If u is a point of E, x may operate at u or may fail. The points of E of successful operation will be called the living space L of x. The complement of L in E, E - L, is the failure space. Estimates of L, and consequently E - L, can be made on theoretical grounds or on the basis of knowledge regarding the components of the instrument x. For an individual x, or class of individuals, a final decision regarding L must rest on trials. Since the number of points of E is, in general, infinite, a study of the behavior of x over E will depend on some form of approximation.

The design space D of an instrument x is the part of its environment E in which it is intended to function. The design problem is the relation between the spaces D and L. The figures 1, 2, and 3 illustrate for the case of two parameters the space relations which are favorable, intermediate, and unfavorable for an instrument. The favorable case is one in which the design space is well inside a substantial living space. There is a relation here to the conventional engineering idea of factor of safety (par 2.5). The intermediate case occurs when the design space is near a critical boundary of the living space L. If the living space has a boundary in common with the space E, points outside E do not come into consideration and these parts of the boundary of L do not count as critical. If D intersects E - L, (fig. 3), design involves a risk determined by the probability of occurrence of points of danger.

While the determination of a living space L is related to simulation, it is to be distinguished from simulation in that simulation usually covers only a small part of the design space.

In choosing the parameters for an experimental determination of an environmental living space, the facts to be established are: (1) whether a given parameter varies during a prescribed operation, (2) if the parameter varies, whether its variation influences the operation of the instrument, (3) if the operation is influenced, whether the variation of the parameter impairs the operation of the instrument, and (4) the bounds of the parameters. Some of these may be partially determined in advance of construction of a model and actual testing, from theory and information regarding components.

For example, there is no evidence that the electrical properties of silicon or germanium crystals are affected by vibration or shock at levels of frequency and amplitude that were applicable to the tests discussed in sections 3 and 4. Thus, in using one of these crystals we would consider the interval of temperature variation, recognizing that germanium is more sensitive to temperatures over 150°F than silicon, but we can neglect the parameters of mechanical vibration.

2.3 Lattices

A finite system of points regularly arranged in a space will be called a lattice. This concept is essential to the test program and the type of lattice to be used is precisely defined as follows. Let $r = (r_1, r_2, \ldots, r_k)$ be a system of k integers satisfying

$$0 \leqq r_i \leqq m \quad (i = 1,2,\ldots,k) \tag{2}$$

for some suitably chosen integer m. Then the points

$$v = (v_1, v_2, \ldots, v_k) \text{ where}$$

$$v_i = a_i + \frac{r_i(b_i - a_i)}{m} \quad \text{and} \quad (i = 1,2,\ldots,k) \tag{3}$$

form a lattice in E of $(m + 1)^k$ points.

The dots in figure 5 represent a lattice of $5^2 = 25$ points in a two-parameter space. The zigzag heavy line is a corresponding path. If each interval of a four-parameter space is divided into four equal parts, the number of lattice points is $5^4 = 625$, a number too large for practical experimentation if each point is to be tested individually. By varying parameters continuously, this difficulty can be avoided (par 2.4).

The following example of a lattice is related to the path of the experiment discussed in section 2. The points of the lattice are $v_{ijk} = (T_i, V_j, P_k)$, $i = 0,1,2,3$, $j = 1,2,3,4,5$, and $k = 0,1,2,\ldots,7$, where

$$\begin{aligned} T_i &= -70;\ 20;\ 110;\ 200^{\circ}\text{F}; \\ V_j &= 50;\ 500;\ 1000;\ 1500;\ 2000 \text{ cps}; \\ P_k &= \text{atmospheric pressure equivalent to that at} \\ &\quad 0;\ 16{,}667;\ 33{,}333;\ 50{,}000;\ 66{,}667;\ 83{,}333; \\ &\quad 100{,}000 \text{ ft.} \end{aligned} \tag{4}$$

The amplitude of vibration is assumed to be constant. This lattice is rectangular. It contains $4 \cdot 5 \cdot 7 = 140$ points. The nearest point of the lattice to a given point of the space L, $p = (T,V,P)$, satisfies the inequalities. ((5) below).

$$|T - T_i| \leqq 45^{\circ}F$$

$$|V - V_j| \leqq 250 \text{ cps} \tag{5}$$

$$|P - P_k| \leqq (8{,}333 \text{ ft})^*$$

Certain values of a parameter may be critical as in the case of a vibration at a natural frequency of x. Such values disconnect the environmental space and the living space falls into parts. Fortunately in these parts the transfer functions are usually bounded and a few observations can effectively determine these bounds.

It is important to note the difference between the environment with t = 0 and that obtained with varying t. In this connection there is the possibility that a part of the environmental space will be invariant in time. For example, if a structure does not change during the time t allowed for a test, it is a time invariant.

2.4 Complete Environmental Testing

The vertices of a lattice in a space E are the corners of a set of rectangular cells that fill the space. Such a set of cells will be called a partition of E. If an instrument x is to be tested over the entire set E, it is possible to define a path u(t) that will pass in succession as t increases through all the cells of a partition. In case the cells are of appropriate size, the variation $\Delta f(x,u)$ of the output f(x,u) of the instrument x over a cell will be small and the function $f[x,u(t)]$ can be regarded as representative of the output of x over the entire space E. If cells exist that do not satisfy the condition -- $\Delta f(x,u)$ small, they may either be excluded from the living space L_x or examined more closely by introducing a further subdivision.

If A is a subset of an environment E, a test program T is said to <u>cover</u> A if the test applies to every point P of A. If the set A is linear, the test is called a linear probe. It is evident that if A is multidimensional with k coordinates for each point and O is a point of A, then a set of linear probes from O obtained by varying each coordinate through its range in A will not cover A. The corresponding tests may not represent the output of the instrument under test for the entire set A. That is, factors sometimes combine to produce effects not produced by a single factor. The failure of linear probes to cover an environment is illustrated by figure 4.

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* The parentheses represent the pressure difference corresponding to this change in altitude at the altitude providing the pressure P_k.

To compare the procedure developed here with a test of a missile, note that its flight path through the environment will not, in general, pass through each part. Thus flight testing may cover only a part of an environmental space. Flight testing does not show the relative strength of the components of a missile; complete environmental testing permits a determination of the relative strength of components.

As previously mentioned, the time t used in a test is a parameter of special significance. The duration of a test is properly determined by a period of use. In the present discussion, t will represent the number of units of time, whether seconds, minutes, hours, days, etc, elapsed from the beginning of a test. If $t = 0$, it is implied that the test is on an "on" or "off" basis, and duration is not a factor.

If x is an instrument and P is a point of its environment, assumed multidimensional, we represent the output of x at P during an instant t of a test by $f(x,P,t)$. This output may be multidimensional, but the conditions for satisfactory performance may be represented by an inequality,

$$C_1 \leqq f(x,P,t) \leqq C_2 ,$$

where C_1 and C_2 represent points of the output space.

Let P be a point of the environment for which an instrument x is to be designed. The following considerations arise. Assume that x is to be in use or under test for a time t units with output $f(x,P,t)$. Then with P fixed, we have for consideration:

1) the expectation of the occurrence of P in the use of x;
2) the severity in relation to x of the environment represented by P;
3) the effect of individual or combined coordinates of P on $f(x,P,t)$;
4) the relation of P to the living space L_x of x;
5) deterioration of $f(x,P,t)$ with increasing x;
6) mean time to failure at P;
7) protection;
8) effect of restrictions on size, weight, shape, materials;
9) cost versus risk;
10) physical laws;
11) feasibility.

The difficulty of resolving the problem presented by these conditions at a single point P, emphasizes the difficulties inherent in a program involving an entire environment E.

2.5 Normalization and Factors of Safety

Let E be a k-parameter space with finite or infinite bounds, $a_i \leqq u_i \leqq b_i$ $(i = 1,2,\ldots,k)$. We may transform each parameter u_i linearly into $\hat{u}_i$ with range $0 \leqq \hat{u}_i \leqq 1$, unless $a_i = b_i$, in which case u_i has the single value zero. If s parameters have this latter property, the image of E in the space E is effectively a cube of k - s dimensions. The (k - s) unit cube E will be called a normalization of the space E.

Suppose now that instead of normalizing the entire environment, we normalize the living space L obtaining a cubical image space L. If D is the corresponding design space and is a subset of L, then we may in the interest of safety require that no point of D, the image of D in L, have a positive coordinate less than 1/4 or greater than 3/4. This requires for the case of bounded parameters a factor of safety of at least two. If the living space is unlimited in any parameter, the factor of safety cannot be estimated in terms of the design boundaries of that parameter. Only theoretical considerations can supply an estimate that a parameter in the living space is unbounded.

Two methods are available for evaluating an instrument over a space. One is to apply random sampling methods and the corresponding statistical procedures (ref 5). This, at best, involves a considerable number of settings of testing equipment. The other is to pass a path through the lattice (fig 5), or the system of cells with lattice points as vertices.

2.6 Component Spaces

A component of an instrument x is any single part of the system that contributes to the successful operation of x. The contribution of a component can be measured even if, as in case of a switch, it has only two values, on and off, as they can be represented by 1 and 0, respectively. A component functioning as a unit will have a living space. Let z be a component of x, and let L_z be its living space. Let L_x be the living space of x. Clearly L_x is part of L_z. Otherwise a point of L_x will be in the failure region of z contrary to the expectation that x is operative at every point of L. This leads to the first principle of design.

<u>The living space of an instrument lies in the living space of each of its components.</u>

In this connection it is necessary to observe that an instrument may protect a component in a variety of ways. For these reasons the living

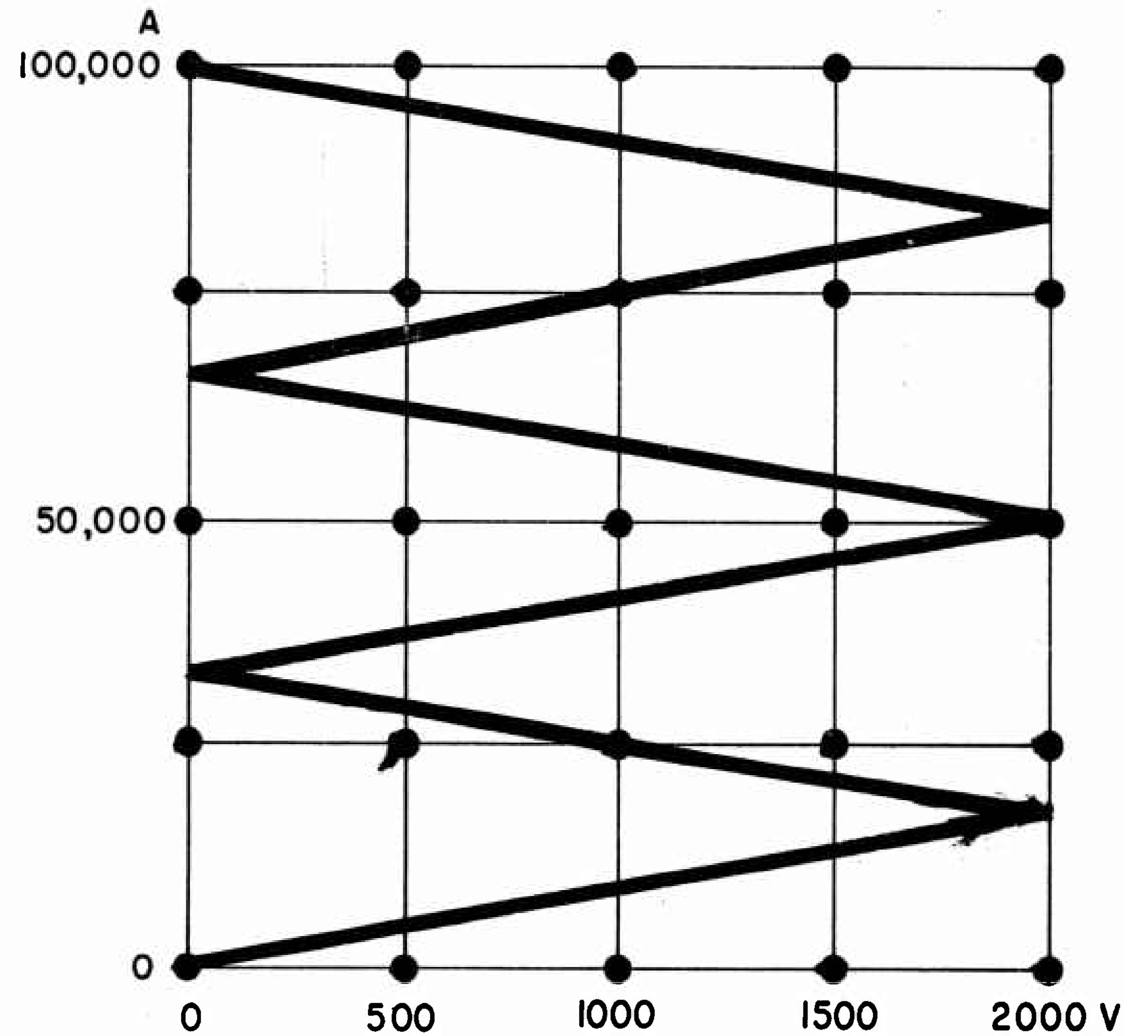

Figure 5. Two-parameter lattice (heavy zigzag line represents a time path through corresponding space).

space of a component is to be interpreted in terms of its protection as a member of a system. Inversely, if the living space of a component is known and it is not safe with respect to the design space D of x, then the degree of protection required can be determined. The converse of this first principle is obvious.

<u>If an instrument x operates in a space L, the living space component contains L.</u>

Thus an experimental study of x may be used to obtain information regarding its components. While, in general, an instrument x will have many components, the following discussion for two is easily extended.

Suppose instruments y and z are components of a system x, and that L_y and L_z are the corresponding living spaces. Thus we conclude: The living space L_x of x with components y, z, is a subset of the intersection of L_y and L_z, in symbols.

$$L_x \subset L_y \cap L_z$$

In general L_x lies in the part common to the living spaces of all its components.

It follows that a logical first step in design is to gather information regarding the living space of prospective components. It is also evident that the problem is usually multidimensional and that, in consequence, one-dimensional probing may not be sufficient.

In the analysis of the role of the living space of an instrument, probabilities may enter in two ways: first, through the mean time to failure at a point, and second, through the probability that the point will occur in use. An estimate of mean time to failure may be based upon a mean time to failure observed for a point of greater strain than the one under consideration. (Normally, there is an expectation that the mean time to failure at the point of interest will not exceed that found at the point of observation.)

2.7 Monotone Functions

The problem of determining a living space can be greatly simplified if the output of an instrument varies monotonically at each point of its living space. By definition: If u $(u_1, u_2, \ldots, u_k)$ is a point of the living space L of an instrument, x and f (x,u) is the measured output of x at u, then f(x,u) is monotone increasing (decreasing) whenever any coordinate u_i of u is increased by a small positive increment and Δu_i, the corresponding value of f(x,u) is not decreased (increased).

Formally, if $u + \Delta u$ is the new value of u

$$f(x,u + \Delta u) \geqq f(x,u) \tag{6}$$

indicates that $f(x,u)$ is monotone increasing, that is, nondecreasing. Figure 6 shows for the case of a function of two parameters the surface generated by a decreasing function. A differentiable function $f(x,u)$ is nondecreasing if all its partial derivatives are nonnegative.

It is possible by a single test to show that a function is not monotone. If all coordinates of $v = (v_1, v_2, \ldots, v_k)$ satisfy the inequalities:

$$u_i \leqq v_i \quad (i = 1,\ldots,k), \tag{7}$$

and for at least one value of i, $u_i < v_i$, then v follows u and we write $u < v$. By use of this definition, the test follows from the following theorem.

If $f(x,u)$ is monotone increasing, for every pair of points such that $u < u'$

$$f(x,u) \leqq f(x,u') \tag{8}$$

For monotone decreasing functions, the inequalities are reversed.

Thus if, for a single pair, the above condition fails, $f(x,u)$ is not monotone increasing. By random sampling a probability of monotonicity can be established; or a space lattice can be explored, in case there is a reasonable expectation that $f(x,u)$ changes slowly with u. If a function $f(x,u)$ is monotone over a k-dimensional rectangular solid S, then $f(x,u)$ has its extreme values at opposite corners of S and two observations will permit a determination of the variation of f over S.

While many functions $f(x,u)$ fail to be monotone over their entire living space, it is frequently possible to partition the space into subspaces in each of which the monotone condition holds. Thus in the case of the amplifier studied in section 3, the very slight change in the mean relative gain observed as altitude increased was monotone increasing in that parameter.

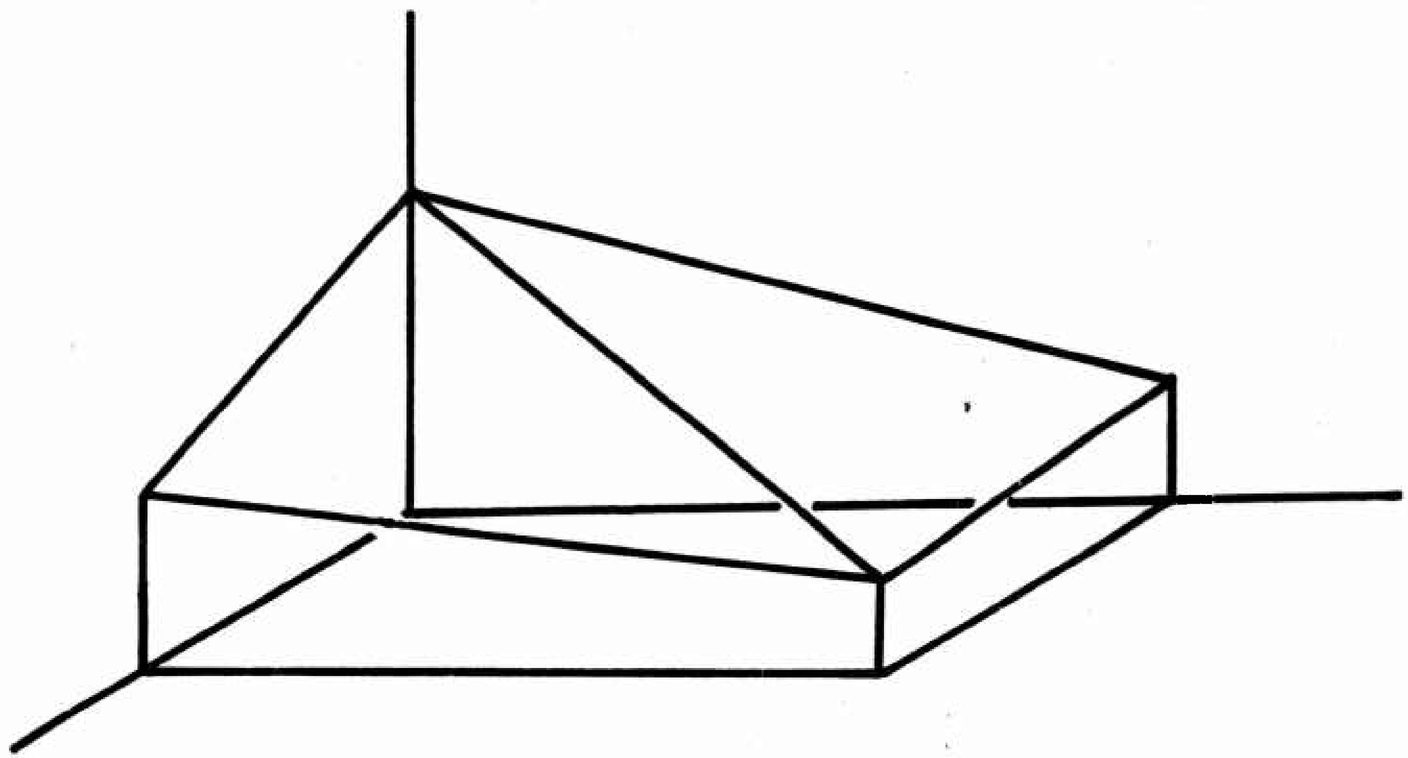

Figure 6. Surface representing a monotone function of two variables.

3. ENVIRONMENTAL TESTS OF IF AMPLIFIERS - FIRST SERIES

3.1 The IF Amplifier

The environmental testing methods outlined in section 2, were applied to a family of IF amplifiers designed at DOFL to have the following characteristics: The amplifier should be readily adaptable to various types of fuzes without major alterations in the shape of the packaged unit. It should be small, stable, rugged, and admit only a small variation in relative gain over a wide variation of temperature and other environmental factors.

Additional information regarding the amplifier is given in appendix A. Two series of amplifiers were tested. The first series is discussed in this section; and the second in section 4 of this report. The amplifiers of the first series had either three or six stages of amplification. Since the six-stage amplifier can be regarded as a system composed of two three-stage amplifiers, the three-stage amplifier can be regarded as a component of a six-stage amplifier (par 2.6 above).

The tests proposed for these amplifiers were in two series. The first series of six tests was to demonstrate that the living space L of these instruments is essentially three-dimensional determined by the parameters T (temperature), V (frequency of vibration at a constant level of acceleration), and P (pressure corresponding to altitudes from sea level to 100,000 ft). These parameters were allowed to vary simultaneously so that a path would pass within a prescribed neighborhood of each point of the space. The tests were conducted in a thermal chamber described in appendix B (fig. B3). This chamber was equipped to provide continuous variation of vibration, pressure, and temperature.

Five tests in the first series were applied to three-stage amplifiers. The sixth test in this series was on a six-stage amplifier, which showed agreement with earlier tests. The recorded ambient temperature of the chamber is the mean of shielded thermocouples suspended near a test object. There is also a thermocouple record of the temperature of air entering and leaving the chamber. The accuracy of the recording and measuring equipment was more than adequate for the tests.

The recording instruments (fig. B4), and the accuracy ratings supplied by the manufacturer, for the controls of the environmental chamber are listed in appendix B. Because the nature of the test permits substantial variations in the parameters, additional calibration of the recorder was not requested. The greatest percent of inaccuracy reported is in the magnitude of acceleration of the electrodynamic vibrator. This could be as much as 5 percent at 20 g, which is less than the observed variations in the recordings.

3.2 Estimated Living Space of the IF Amplifiers

It was the expectation of the designer of the IF amplifier, based on previous one-dimensional tests of the components, that the space determined by the inequalities given below would be within a living space L of the amplifier.

$$
\begin{aligned}
-70^{\circ}F &\leqq T \leqq 200^{\circ}F \\
50 \text{ cps} &\leqq V \leqq 2000 \text{ cps} \\
14.7 \text{ psi} &\leqq p \leqq 0.16 \text{ psi}
\end{aligned}
\qquad (8)
$$

The acceleration was to be maintained at 20-g rms, within limitations of the controls. The choice of 20-g rms as a constant was in the interest of simplicity and was based on previous tests of the electron tubes (ref 6 and 7). (The estimated strength of components suggested the use of this amount of energy.)

Since the concepts relating to environmental space were developed after the amplifier was designed, there was no planned design space D. However, the space defined above is expected to include the conditions that would be met by an amplifier during a flight of a guided missile through the atmosphere with a maximum range of 500 miles. Accordingly, the rectangular environment specified by the inequalities given above was based upon these conditions and used for the tests in the first series.

Figure 5 illustrates the principle underlying the testing program for evaluating the output of an instrument over a multidimensional space. The heavy line in the diagram represents the path obtained in a two-parameter space by simultaneously varying vibration frequency and altitude (pressure) according to the pattern described above. In the following discussions, the amplifier will be said to be tested over a path in the three space of inequalities (8) and each test will be called a flight.

3.3 The Test Schedule - First Series

The program for the first series of tests was in four 1-hr units, permitting 1 hr at each of four temperatures, $-70^{\circ}F$, $20^{\circ}F$, $110^{\circ}F$, $200^{\circ}F$. During each hour at constant temperature, vibration was held at an acceleration level of 20-g rms, with frequency sweeps from 50 cps to 2000 cps and return at 20-min periods (fig. 7). During the constant-temperature hours, the pressure was reduced from (0 altitude) 14.7 psi ambient (altitude 100,000 ft) to 0.16 psi (fig. 8). At the close of the hour the operation of the amplifier continued during the return to sea level pressure and the temperature change. During the temperature change, the electro dynamic vibrator was turned off to avoid more than 4 hr of vibration.

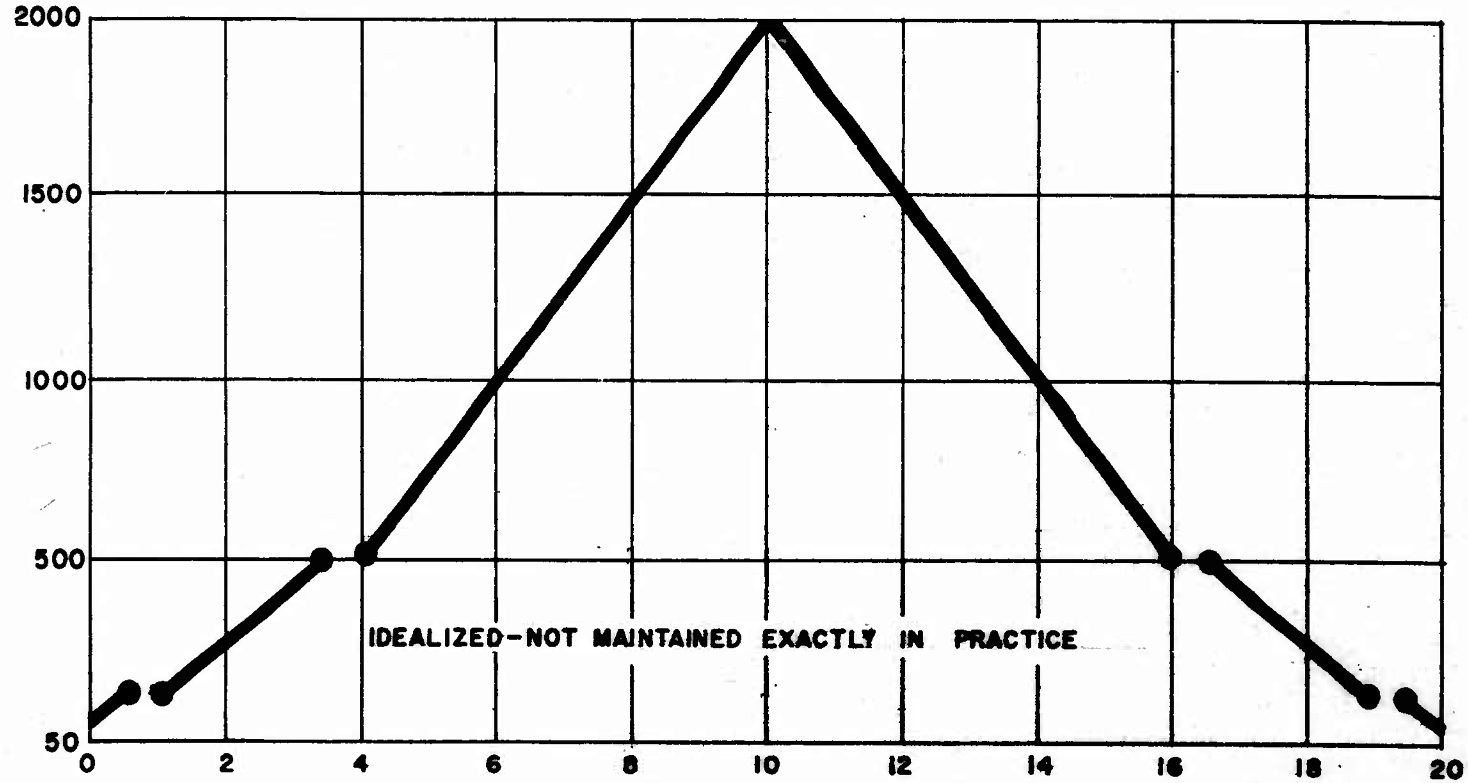

Figure 7. Approximate distribution of frequencies in a 20-min cycle -- first series of tests. (Vibrator was turned off for switching four times in each cycle.)

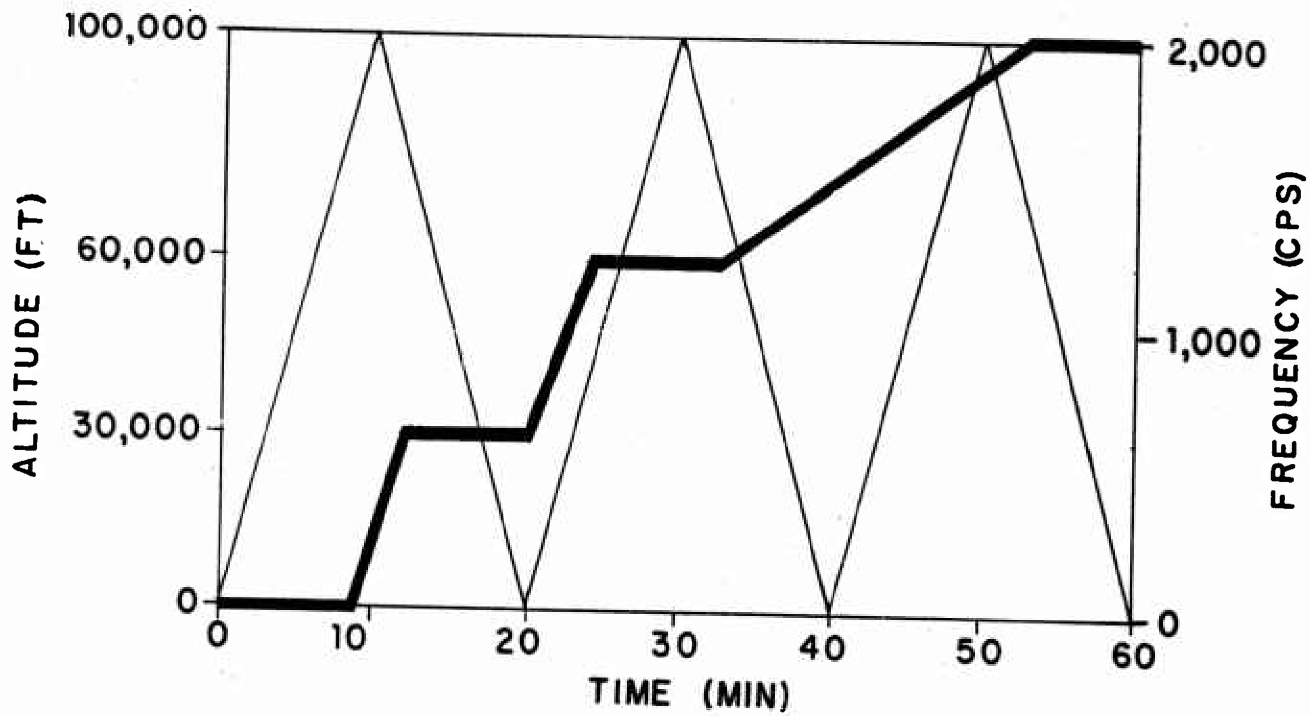

Figure 8. Plan for simultaneous variation of pressure and frequency --- first series of tests.

The output of the amplifier was monitored by an oscilloscope calibrated at each observation of center frequency, bandwidth, and relative gain. Errors in the oscilloscope trace and in the readings are far below noise level of the amplifier. A typical response curve is shown in figure 9.

The oscillograph readings were taken at intervals of 10 or 15 min. These readings changed slowly, and the oscilloscope showed a steady output. Since frequency and pressure were varied continuously and there were many more values of pressure and frequency recorded than readings of gains, it was necessary, in order to represent the influence (if any) of pressure and frequency changes fairly, to interpolate between the readings obtained from the gain of the amplifiers. The interpolations made are on the basis of elapsed time, under the hypothesis that the variation of the output is approximately linear over the time intervals between observations. Except for irregularities arising from malfunctioning of the amplifier or the testing machinery resulting in the elimination of corresponding observations, this hypothesis of linearity seems amply justified.

The test program included a provision that three mutually perpendicular planes of vibration be used, but only one plane in a single run. Consequently a single amplifier would be tested in only one plane of vibration.

3.4 Analysis of Test Results

The results obtained in the combined environment agree with those of previous tests of tubes and other components (ref 6, 7, 8, and app A). There is the expected sensitivity to temperature changes, but none apparent due to changes in ambient pressure, frequency of vibration, or acceleration. There is an expected tendency for the gain to reach a maximum at moderate temperatures and a minimum at extremes of cold or hot (ref 9).

One of the major questions concerning a design is whether it will survive in its design space. Consequently the production of a model that meets this requirement is an important step. It appeared that the test proposed for the first series was adequate. This test was successfully passed in two cases and in a substantial part by others.

The following considerations are significant. The tubes were from a class that had survived 20 g at 700 to 1000 cps for 24 hr. In fact, the present tests indicate that they will endure acceleration of 40 g without loss of output. Since the living space of the tubes had not been completely determined *a priori*, we may apply the results obtained in these tests and assert that the living space of the tubes, when rigidly mounted in aluminum mesh holders in a niche of an aluminum box, is at least as large as the space of these tests.

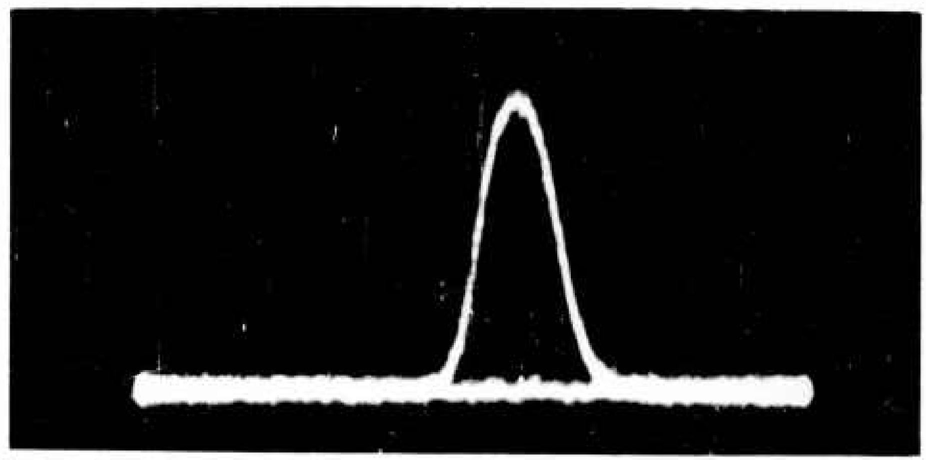

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Figure 9. IF amplifier response curve

$f_o \approx 60$ Mc

BW = 4 Mc, gain 109 db

Figure 10 shows the mean loss of gain for each of 4 hr at constant temperature for a group of three-stage amplifiers. The effect of varying a single parameter is presented in paragraphs 3.5 through 3.9.

3.5 Temperature Effects

In general, the output of the amplifiers varied within the 3-db limit over the temperature range -70°F to 200°F, regardless of the variation in other parameters. There was usually a degradation in output during the hours at extreme temperatures (ref 9). The amount of variation changed somewhat with conditions and some amplifiers varied more than others. The tabulated results show clearly that the instruments were temperature sensitive, being more sensitive to 200°F than to -40°F. Table 1 shows the mean output for each hour of steady ambient temperature for the three-stage amplifiers of tests 6 and 7, series I; typical performance curves are shown in figure 11. The mean output of the six-stage amplifier of series I (test 8) is given in table 2; graphic data are presented in figure 12.

Table 1. Performance of Three-Stage Amplifiers

Hour	Central frequency (Mc)	Bandwidth (Mc)	Loss of gain (db)	T12 ($^{\circ}$F)
I	60.3	5.2	0.2	-40[a]
II	59.3	5.0	0.0	23
III	58.6	5.0	1.1	111
IV	58.1	5.0	3.0	190

[a] While -70° was the planned mean temperature, the equipment available was unable to hold the chamber at this temperature.

Table 2. Performance of Six-Stage Amplifiers

Hour	Central frequency (Mc)	Bandwidth (Mc)	Loss of gain (db)	T12 ($^{\circ}$F)
I	59.9	2.7	1.2	-72
II	58.2	2.7	0.0	24
III	57.5	2.4	0.45	107
IV	56.8	2.6	1.8	197

In a test of a three-stage IF amplifier used previously in a thermal chamber test over a temperature range of -60°C to +100°C the loss of gain varied from 1.3 db through a minimum of zero (reached

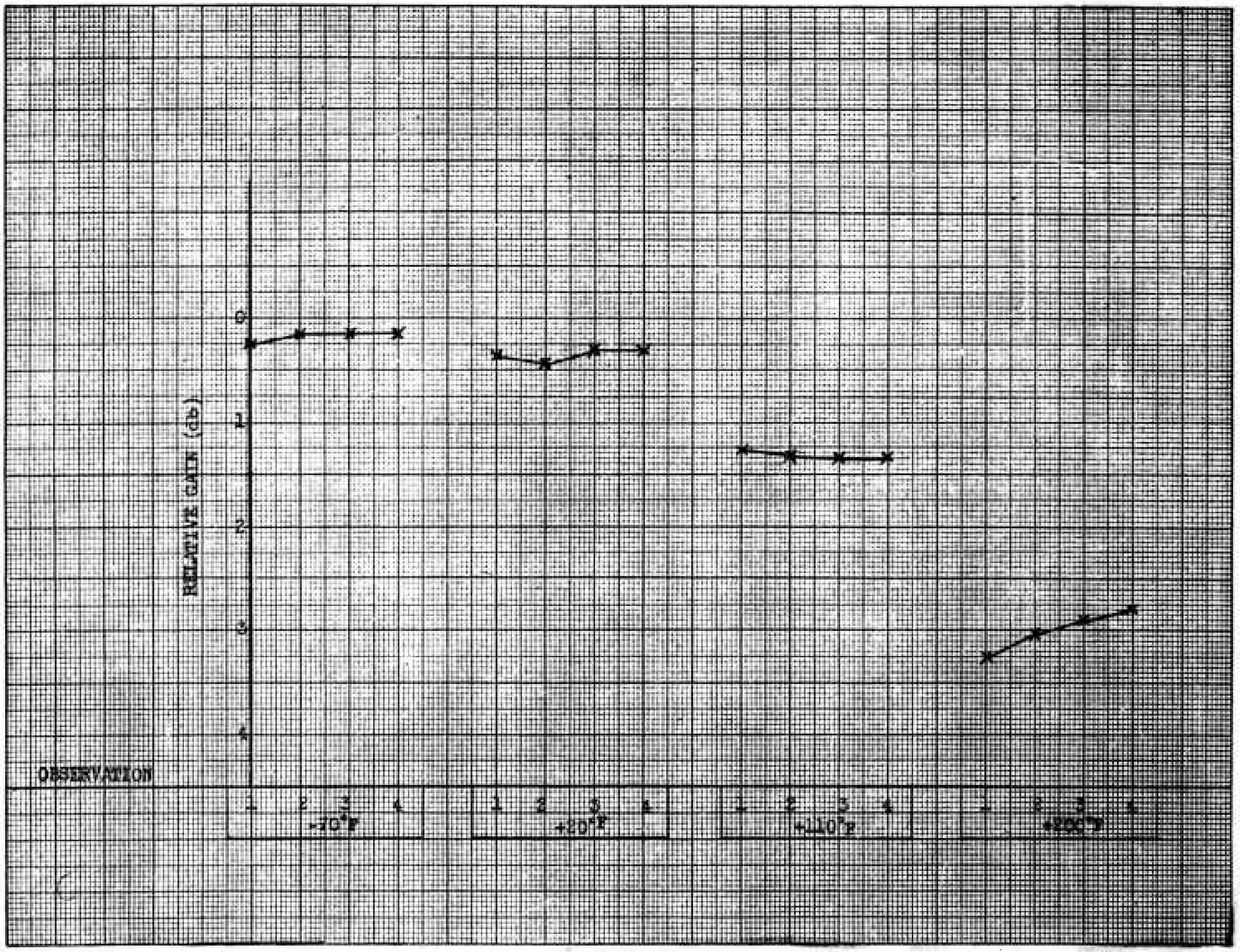

Figure 10. Relative gain (db) for each of four observations at constant chamber temperature (three-tube amplifiers).

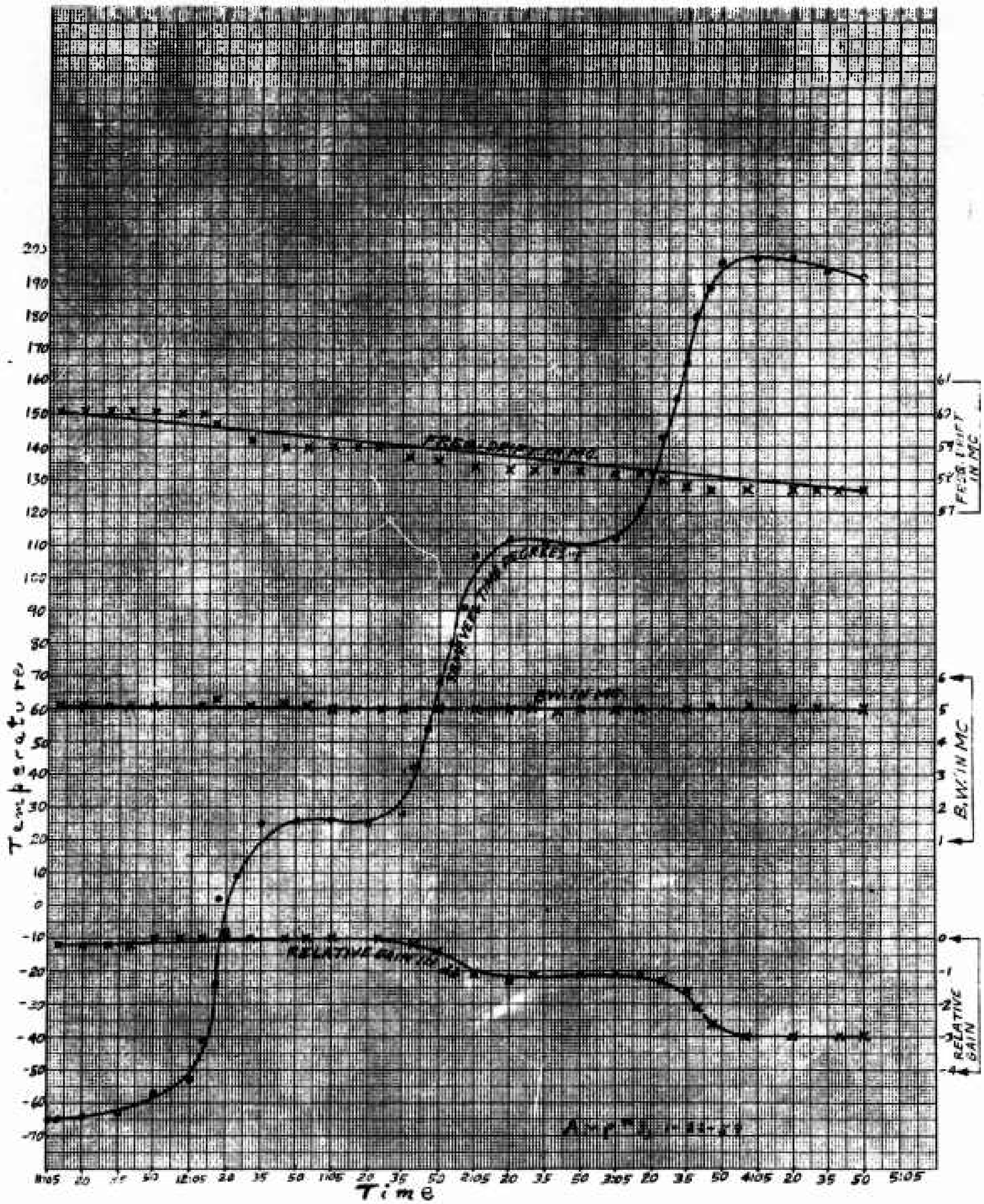

Figure 11. Typical performance curves for three-stage amplifier, series I.

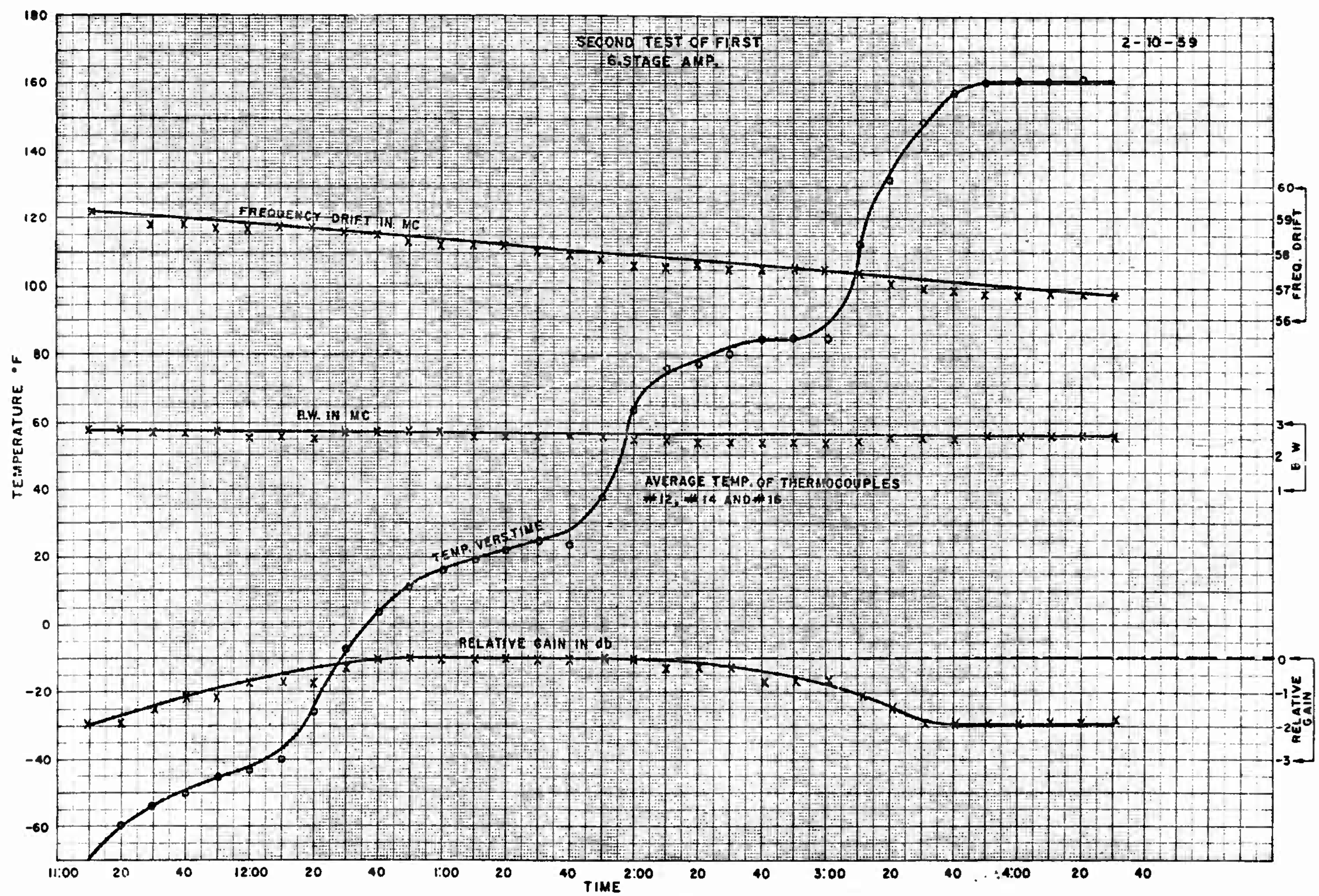

Figure 12. Typical performance curves for six-stage amplifier, series I.

at 10°C) to 3 db at 100°C. The time of the test was 2 hr and 45 min. This test represents the expected behavior of the amplifier under temperature changes with other environmental factors constant.

3.6 Ambient Pressure

Table 3 shows that the gain of the amplifiers in test series I was essentially independent of the ambient pressure.

Table 3. Variation in Mean Loss of Amplifier Gain (db)

Altitude (10^3ft)	Temperature -70°F	10°F	110°F	200°F	Mean
Sea Level	0.22	0.06	1.38	4.40	1.35
25 ft	0.13	0.06	1.31	4.72	1.37
50 ft	0.13	0.04	1.16	4.54	1.29
100 ft	0.06	0.00	1.12	5.11	1.35

3.7 Frequency of Vibration

The amplifiers of tests 6, 7, 8 of the first series completed the test with relative gain variations within the 3-db margin, an arbitrary standard. The observations made at intervals of 10 or 15 min required that the relative gain for a given frequency be obtained in many cases by interpolation. While direct inspection of the oscilloscope indicated that the 20-min sweeps in frequency from 50 cps to 2000 cps and return had no effect on output, table 4 of mean loss of gain (based on tests 6, 7, 8 of series I) is additional evidence.

Table 4. Mean Loss of Gain of Three Amplifiers tested in Series I

Vibration frequency (cps)	Mean loss of gain (db)
50	0.92
1000	0.92
2000	0.92

The distribution of variations in loss of gain is not normal because when a maximum is reached, the only direction of change in gain is downward. Also, before a maximum is reached, the trend in gain is consistently upward. Thus, variations in sweeps do not influence the trend. If they influence the amount of change, no evidence is available.

Some vibration periods at constant temperature showed no variations in relative gain readings. When a substantial variation in gain was observed, it was in agreement with the trend of the gain curve i.e., up from cold to middle range, and down from middle range to hot. Reversing the temperature range produced the corresponding pattern. Thus, while a number of hours during vibration showed no effect from that cause, the hours in which changes occurred were not otherwise equal. That is, either temperature varied or the amplifier was out of order.

3.8 Time and Order

The influence of the time factor is evaluated by comparing the amplifier output at different times under otherwise equivalent environmental conditions. This comparison was helped by running the tests from cold to hot and then reversing the order. Since vibration was changed continuously in the first series and g-level changed every 20 min during the second series, a variety of such comparisons is possible. Table 5 shows that the order of reversal from cold-hot to hot-cold caused no significant variation in output.

Table 5. Average Values of Mean Loss of Gain (db) per Hour for Three Amplifiers of the First Series at Different Times

Hour at constant temperature	Temperature varied from cold to hot	Temperature varied from hot to cold
I	0.7	1.9
II	0.0	0.9
III	0.8	0.1
IV	2.4	0.3

3.9 Failures

Several tests were incomplete because of electronic component breakdown or instrumentation failure, e.g., compression failure and vibration failure. Some tests were stopped for mechanical reasons and resumed later. This procedure was regarded acceptable because amplifier performance proceeded normally after the halt and no significant additional strain was imposed. Results of tests that were not completed because of breakdowns in equipment are omitted from the averages. However, they did contribute to the total number of hours of satisfactory operation under test conditions.

4. ENVIRONMENTAL TESTS OF IF AMPLIFIERS - SECOND SERIES

4.1 Objectives of the Tests

The information from the first series of tests was the basis for the design of a second series of tests to examine the amplifiers under a more severe environment. The space of series I was used with the expectation that it would lie within the living space of the amplifier. Since this proved to be the case, the space of the second series was made more severe to gain information regarding the limits of the living space.

4.2 Environmental Space

Since the first series of tests indicated that frequency of vibration and variations in atmospheric pressure did not influence the output of the amplifiers under test as long as they were in undamaged condition, it was decided to omit these variables from the second series of tests and introduce greater intensity of vibration, as well as a broader temperature range. The variables of the second series of tests, in addition to time, were temperature T, acceleration V, and humidity. The ranges were:

$$- 100^{\circ}F \leqq T \leqq 200^{\circ}F$$

$$V = 5\ g,\ 20\ g,\ 40\ g$$

4.3 Test Schedule for Second Series

In the second series of tests the schedule was as follows: part of the tests began at high temperature and proceeded to low, the remainder ran the temperature in reverse order. This was to study any effects of change or order of events. For the test from low to high temperature, the first hour the temperature of the chamber was held at $-100^{\circ}F$ (ambient). The electrodynamic vibrator is run at 5 g for 20 min, 20 g for 20 min and 40 g for 20 min. The next 2 hr were used to bring the ambient temperature to $200^{\circ}F$, where it was held for an hour. During each hour of the test the cycle prescribed for the vibrator during the first hour was repeated. In tests #10-13 of this series steam was injected in the covering hood during the hour at $200^{\circ}F$ to provide a saturated condition for the ambient air.

The following chart shows the arrangement of the second series of tests with respect to orientation, order, and humidity. To study the effect of orientation on the operation of the amplifiers three mountings were used: (1) horizontal; (2) on a side; (3) vertical.

4.4 Analysis of Test Results

The general remarks of paragraph 3.4 are applicable to this analysis. Figures 13 and 14 show temperature and relative gain of six-

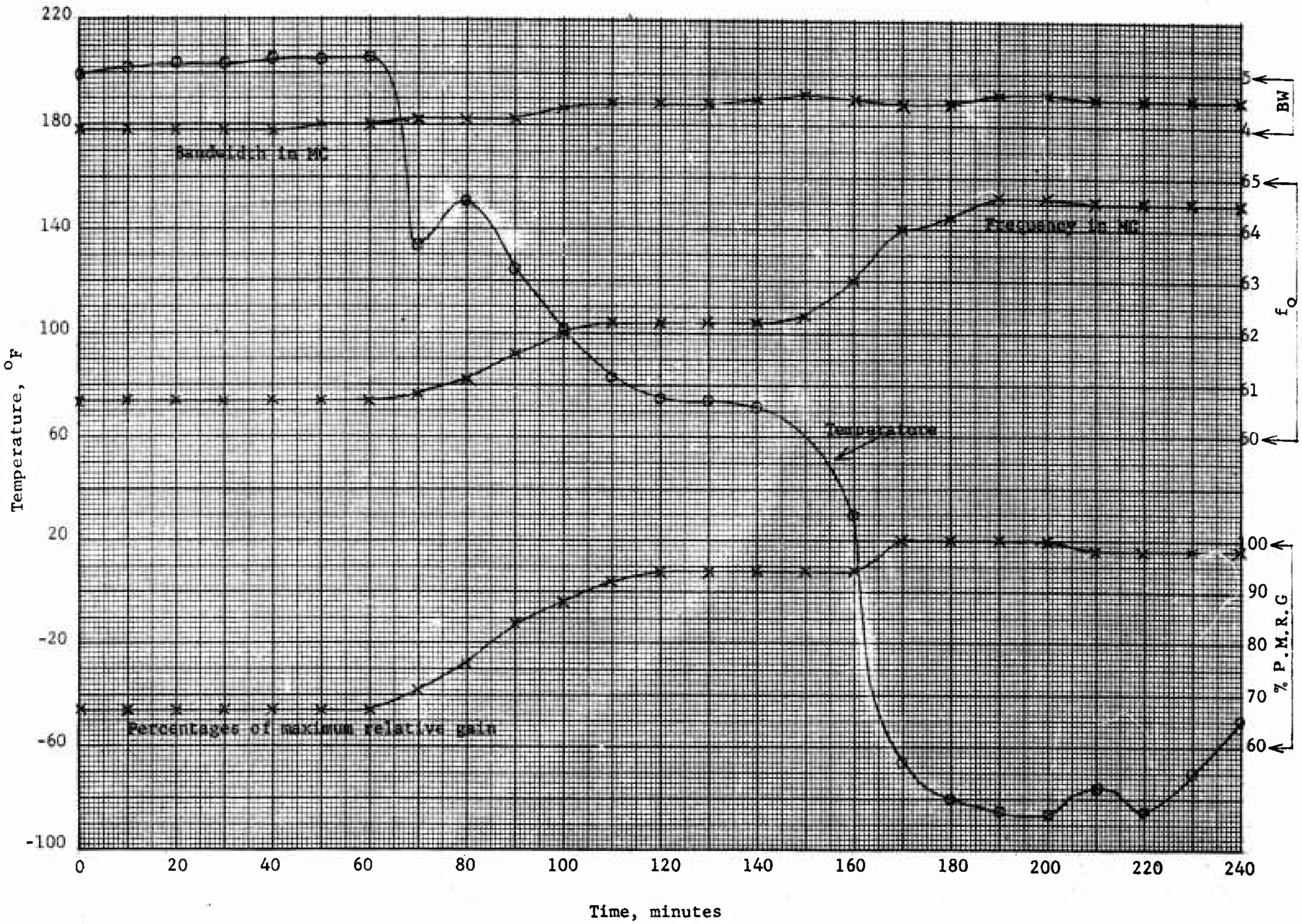

Figure 13. Performance curves for six-tube amplifier 6-B, series II, test 1.

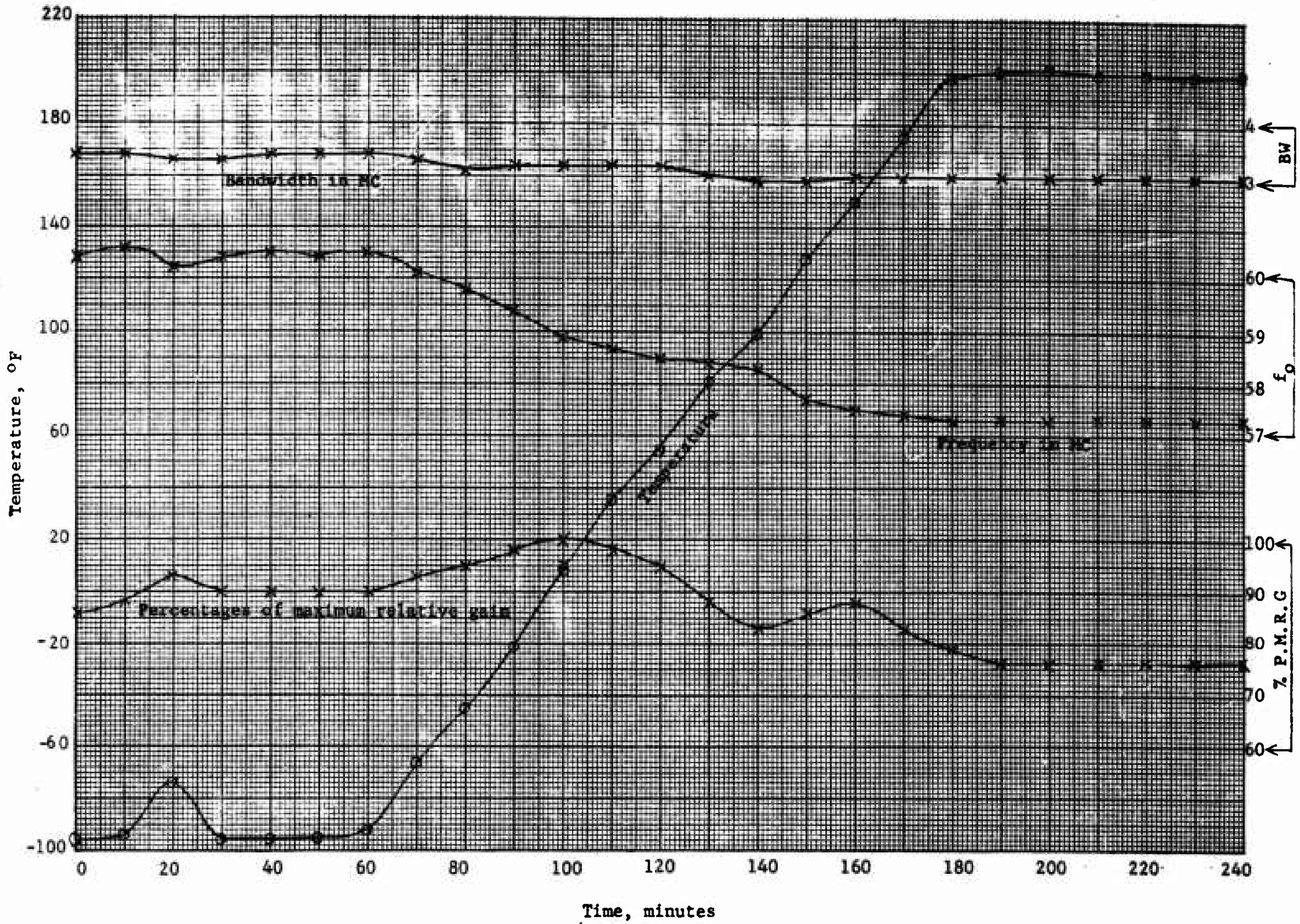

Figure 14. Performance curves for six-tube amplifier 2-A, series II, test 9.

Chart I. Schedule of Tests Series II

Test	Amp. No.	Orientation	Order of Temperature Variation	Humidity
1	6B	1	Hot to cold	
2	8A	2	Hot to cold	
3	8B	3	Hot to cold	
4	4B	1	Hot to cold	
5	3B	2	Hot to cold	
6	7	3	Cold to hot	
7			Cold to hot	
8	3	2	Cold to hot	
9	4	3	Cold to hot	
9A	4	3	Cold to hot	
10			Cold to hot	Humidity
11		1	Cold to hot	Humidity
12	12	1	Hot to cold	Humidity
13		2	Cold to hot	Humidity

tube amplifiers versus time. Figure 15 presents a comparison of relative gain for tests 1 and 9 plotted against temperatures recorded inside the amplifier case. Paragraphs 4.5 through 4.9 present an analysis of the results of the second series of tests.

4.5 Temperature

Wider variations in output were expected from the increase in the temperature range. Over the range $-100^{\circ}F$ to $210^{\circ}F$ the loss of gain tended to vary below the arbitrary limit of 3 db proposed. However, this variation is within the expected limits of the temperature-dependent component values and apparently is independent of the variables of vibration and time. High temperature combined with humidity

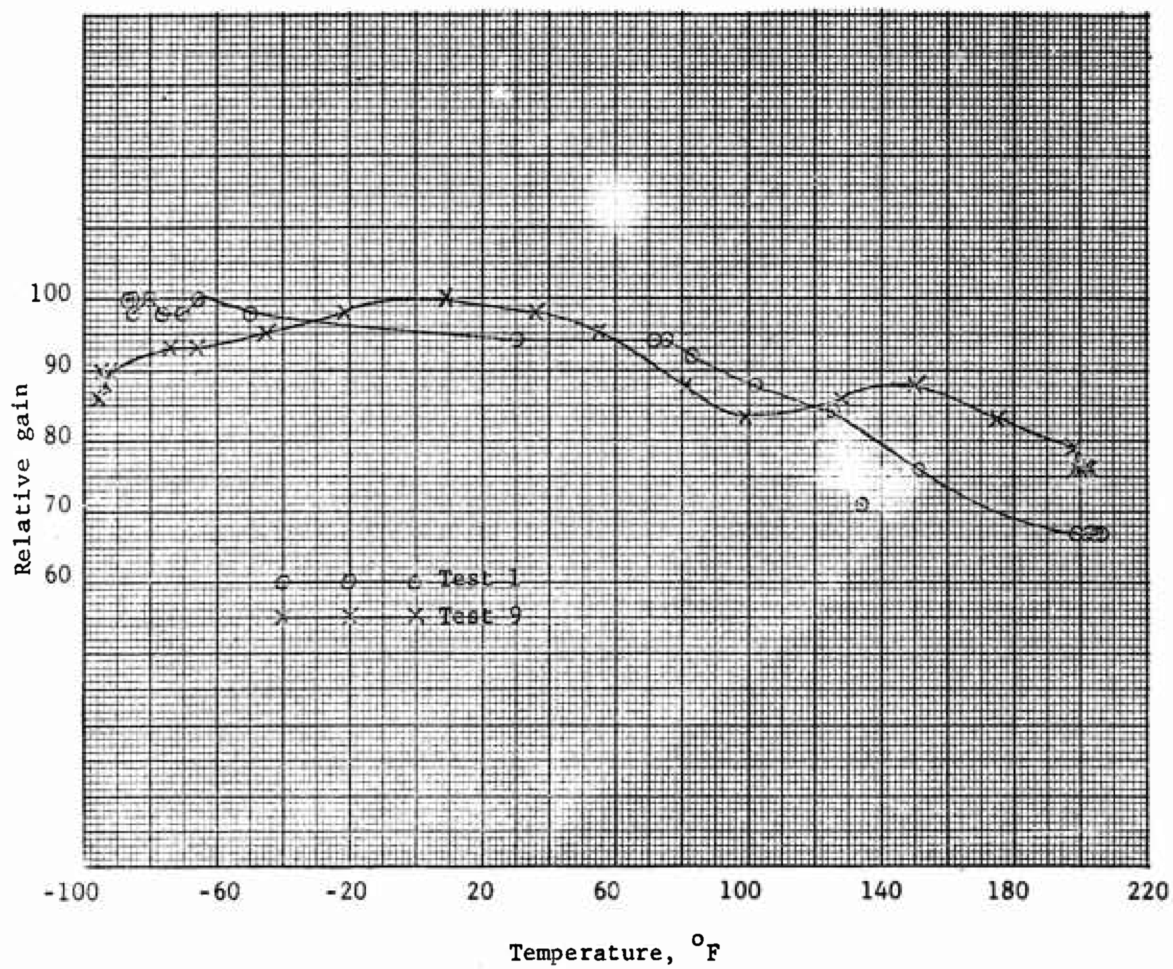

Figure 15. Variation in percentage of relative gain with temperature for tests 1 and 9.

in four tests showed a variation that may have been caused by the high humidity. The testing was insufficient to permit a determination of the cause of the observed change.

Table 6 shows the average effect of temperature for thirteen tests of the second series for hours of constant temperature. The gain was constant for hours while both temperature and vibration varied.

Table 6. Averages for Tests 1 through 13 Series II by Hours

Temperature of chamber	Center frequency	Bandwidth	Loss of gain
(°F)	(Mc)	(Mc)	(db)
-87	61.1	3.5	1.3
-17	60.1	3.4	0.5
82	59.2	3.2	1.7
203	58.3	3.16	4.4

4.6 Level of Acceleration

To verify the ability of the IF amplifiers to withstand a high level of acceleration during an environmental test, a three-stage amplifier that had previously survived a test program as outlined in paragraph 3.3 was tested in a vibrator for 3 hr at accelerations from 20-g to 60-g rms without showing any deterioration in output. On the basis of this experience it was decided to conduct the second series of tests by varying acceleration up to the maximum (40 g rms) available for the vibrator used and, also, to omit continuous variation of frequency of vibration.

The mean loss of gain has been computed for each of eleven tests of the second series separately for each of the acceleration levels 5, 20, and 40 g. These averages have been found for the 1 hr at minimum temperature, the 1 hr at maximum temperature, and the 2 hr allowed for the temperature change. In addition overall averages were found. The figures obtained show slight differences between the outputs recorded for the different levels of acceleration, and these differences are within the estimated errors of observation. These results are presented in table 7.

This table shows that within the range 5-g to 40-g rms the level of acceleration has no direct influence on the output of this family of IF amplifiers. The vibration sequences are given in detail in paragraph 4.3.

Table 7. Variation in Mean Loss of Gain for Different Levels of Acceleration

Level of acceleration	Mean loss of gain at minimum temperature, -87°F	for period of rising temperature, 48°F	at maximum temperature, 203°F
(g)			
5	1.2	1.01	4.0
20	1.2	1.11	4.0
40	1.3	0.92	4.3

4.7 Effects of Orientation on Amplifier Gain

In tests 1 through 13 of the second series each amplifier was mounted in a position determined by the number of the test. The three positions used were (1) flat, (2) on side, (3) on end. In each position the accelerometers were mounted so that the greatest attained acceleration would be represented by the assigned reading. Since tests 6, 7, 8 were not complete and test 9A was an accidental rerun of the amplifier of test 9 with the same setting, the final distribution of positions was:

Position 1. Tests 1, 4, 10, 11, 12

Position 2. Tests 2, 5, 13

Position 3. Tests 3, 9, 9A

Table 8 shows the mean loss of gain for the three groups of tests for the hot hour, the cold hour, and the 170 minutes between the temperature extremes. No reliable conclusions can be drawn from this table regarding the hypothesis that position influences the gain of an amplifier, because of the amount of variation shown in the second two columns of the table. The average loss of gain shows slight variations as the position is changed.

Table 8. Mean Loss of Gain (db) for Amplifiers in Different Planes of Acceleration

Test group	Hot hour	Cold Hour	Intermediate	Av
1 (flat)	4.6	0.8	1.2	2.0
2 (on side)	4.9	1.2	0.8	2.1
3 (on end)	3	2.0	1.0	1.0

4.8 Humidity

In the last four tests of the second series, numbers 10, 11, 12, and 13, during the hour at high temperature (ambient temperature above 200°F), steam was introduced into the chamber to produce approximately 100 percent humidity. The mean loss of relative gain of this set of four amplifiers during the hot hour was 5.2 db. For six amplifiers operated during an hour at high temperature without humidity the mean loss of relative gain was 3.8 db. This indicates a possibility that at 200°F high humidity increases the degradation in the output usually observed at that temperature.

4.9 Time and Order

Table 9 shows that reversal of order from cold-hot to hot-cold caused no significant variation in output. A comparison of test 4 (hot to cold) with test 9 (cold to hot) indicates an absence of effect due to time (fig. 15).

Table 9. Mean Loss of Gain for Amplifiers of the Second Series at Different Times

Temperature	Test No.	Time (min.)	Mean T (°F)	Mean loss of gain (db)	Overall mean loss of gain (db)*
Cold hour	1-5, 12	180-240	-88	1.5	2.16
	9-11, 13	0-60	-80	1.5	
Hot hour	1-5, 12	0-60	230	4.6	1.94
	9-11, 13	180-240	204	4.4	

* The figures in this column are the averages of loss of gain (db) for the indicated tests covering the entire 4 hr of testing.

5. SUMMARY AND CONCLUSIONS

5.1 Test Results

The method of complete environmental testing presented in section 2 was applied, in two series of tests, to a family of 20 IF amplifiers with satisfactory results. The two series were somewhat differently motivated. The environmental space of the first series was designed to be a living space and was conservative with respect to the estimated strength of the components of the amplifier. Part of the test series was designed to illustrate a component effect. For this reason, five three-stage amplifiers were tested. It was shown that the environmental space of the tests was substantially within the living space of the three-stage amplifiers. Then a six-stage amplifier was shown to have the corresponding properties, in agreement with the principle that the living space of a system is determined by the living space of the components. However, it must be recognized that the mode of assembling the components of a system is itself a component subject to evaluation. In combining electrical elements the problems of protection and interference are of considerable significance. It was found that for the factors, temperature, ambient pressure, frequency of vibration, acceleration, and time, the living space of the amplifiers was in agreement with estimates based on available information regarding their components.

No evidence of significant effects on output due to ambient pressure, level of acceleration (rms), frequency of vibration (50 to 2000 cps), or time (up to 4 hr) was found. Change of position and order had no observed effect.

The results of the tests in the first series led to a desire for a test of the amplifier over a wider range of temperature and acceleration. Because ambient pressure (that at sea level to 100,000-ft equivalent) did not affect operation and the same was true of frequency of vibration, it was decided to omit consideration of these factors in the second series. As there was evidence from a special test that the system would endure an acceleration of 40 g, the new series provided for the use of acceleration limits of 5 g, 20 g, 40 g. Because of environmental equipment limitations, the humidity tests was applied to only four amplifiers at 200°F and in the one case, saturation of the ambient atmosphere. The principle part of the second series of tests involved the passage of a path through a two-dimensional temperature-acceleration space.

5.2 Relation of Complete Environmental Testing to Reliability

The application of the methods of testing developed in section 2 contributes to reliability in the following respects:

1) The living space of the amplifiers includes the design space; that is, amplifier performance exceeded the design requirement.

2) It was shown that the amplifiers were insensitive to a variety of combined environmental conditions.

3) The amplifier system behavior corresponded to known characteristics of its components.

4) The tests provided quantitative information, previously unavailable, regarding the ruggedness of components of the amplifiers.

5) All amplifier failures were traced to definite component weaknesses.

5.3 Evaluation of Method

The development of methods of testing combined environments is steadily increasing. These methods are especially useful for the evaluation of complex systems during the design stage and have the advantage of inspiring confidence in a newly created instrument. The method proposed here for passing a path through a complete set of subdivisions of an environment has not been applied systematically elsewhere. However, this method has the disadvantage of complexity of apparatus and the need for automatic controls, as well as for training of operators and supervisors. Since component failure is enormously important, this type of testing can provide a basis for the reduction of component failures.

Complete environmental testing provides the following information:

1) The instrument is or is not able to pass the test. This requires operation in a prescribed neighborhood of every point of the environmental test space, plus a duration factor. Surviving the test once is proof that the test space is within the living space of the instrument.

2) The output of the instrument can be estimated for the entire multidimensional space of the test.

3) It is possible through a small number of repetitions to gain information regarding any effects of a change in the order of occurrence of environmental conditions.

4) The factors and their intervals of variation that influence the observed changes in output must be determined, and the amounts of the calculated effects must be established.

The principal feature of this method of testing is that it provides in a laboratory a more complete simulation of an environment than that obtained from the usual method of varying a single environmental factor at a time.

6. REFERENCES

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Appendix A -- IF AMPLIFIER

A1. Properties of the Amplifier

The amplifier should be readily adaptable to various types of fuzes without major alterations in the shape of the packaged unit; it should be small, stable, rugged, and admit a small variation in relative gain over a wide range of variation of temperature and other parameters.

In detail, the planned electrical characteristics of the amplifier are: center frequency (f_o) 60 Mc, bandwidth (BW) 3.5 Mc, amplifier gain approximately 110 db, low noise figure, fixed tuned coils. Automatic gain control was not incorporated in the amplifier because it would interfere with the observation of environmental effects on performance.

The three-stage amplifier has the same center frequency as the six-tube. Its bandwidth is five Mc and its expected mean gain 50 db.

Special features of the amplifier are: all components of the amplifier except tubes are mounted on a single board; the tubes are held rigidly in niches in the aluminum chassis of the amplifier by aluminum wire mesh holders; the circuit board is held in place with epoxy resin potting compound that contributes rigidity and protection from exterior contamination. The use of the single circuit board combined with the potting procedure permits visual inspection of the circuit before final assembly. All components used were commercially available. The dielectric constant of the potting compound used (an epoxy resin) varies from 3 at -70°F to approximately 4.8 at + 200°F. Therefore a shift in center frequency can be expected with changing temperature. However, it is felt that the shift due to temperature of approximately 2 Mc, as has been encountered in past tests, is only partially caused by the change of the dielectric constant of the potting compound. The other cause has not yet been fully determined. No adverse effect on gain could be attributed to potting.

Figure A1 is a photograph of this amplifier in its aluminum case before potting. The cover of the case is firmly fastened while the amplifier is under test so that the only connection with ambient atmosphere is through the holes admitting electrical connections. That the potting effectively prevents atmospheric effects due to variations in pressure below 14.7 psi is evident from observations on the output of the amplifier. Figure 8 shows a typical response curve of the amplifier.

The tubes used belong to a family from which a sample of ten withstood 24 hr of vibration at a frequency of 700 to 900 cps, and acceleration of 20 g, without failures. Before environmental testing, each amplifier was inspected and given bench tests for central frequency, bandwidth, and amplification, both before and after potting.

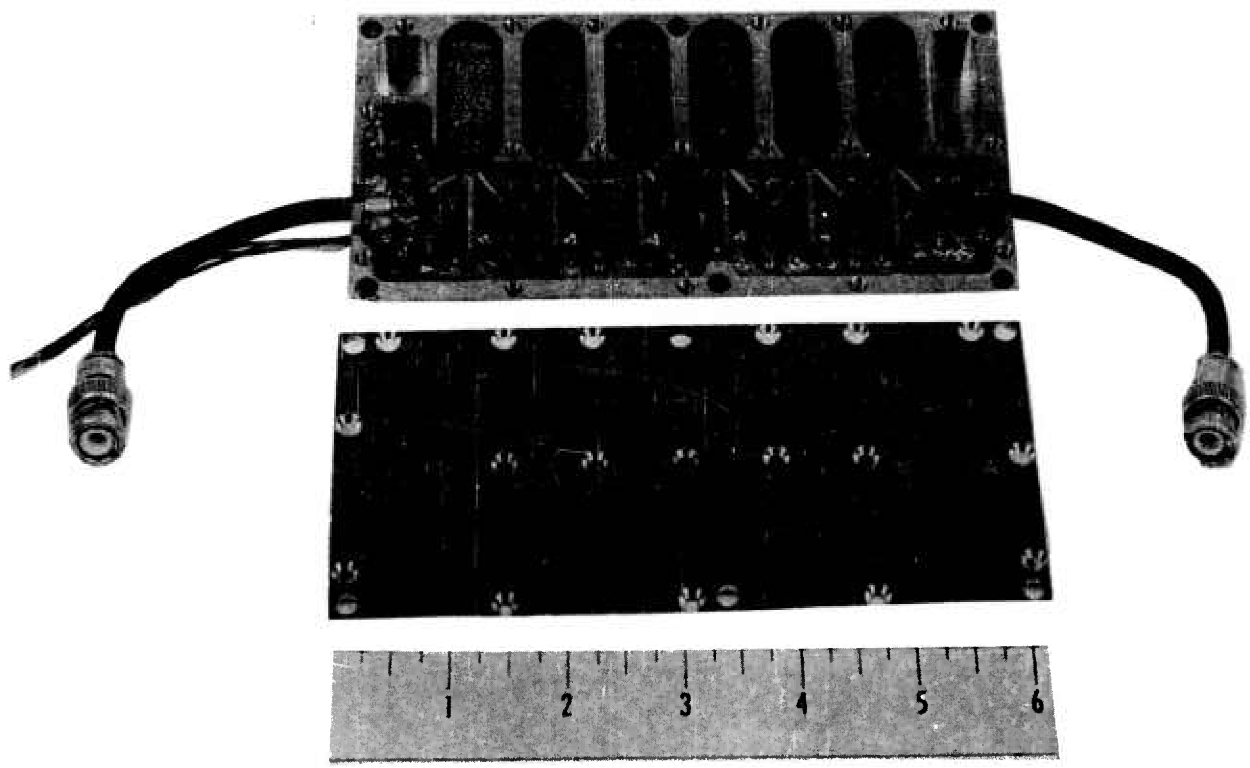

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Figure A 1. Six-stage IF amplifier

A2. Properties of the Amplifier Components

In most cases the figures given below were obtained from bench tests. The normal temperature range of the capacitors used is -60°C to 125°C. The working voltage is 500 v dc. The insulation resistance is 1000 meg after 100 hr at 95 percent relative humidity.

The resistors used in the amplifier circuits have the following properties (ref 6): the maximum change in resistance from that at 25°C is +15 percent at -55°C and +10 percent at 110°C; the resistance change is less than 2 percent after five cycles (+25° to -55°C to 85°C to 25°C); and 0.5 w resistor has at 70°F ambient a maximum dissipation of 1.5×10^{-2} w; in 118 hr at 95 percent relative humidity temperature 55°C, the resistance change is less than 10 percent; leads immersed in solder to 1/8 in. of body at 350 deg for 3 sec produced a change in resistance of less than 3 percent; potting in epoxy resin reduced resistance of 25 resistors tested a maximum of 3.7 percent over a wide range of currents; shock tests produced little effect on resistance. The insulation used in rf connectors is Teflon with a melting point of 620°F. The voltage breakdown of connectors used is 500 v.

The printed circuit base has physical and electrical properties beyond those required by the amplifier in use. Safe operating voltage between conductors is 7,000 v/in. The printed conductors will carry 5 amp; the maximum current used is 1.2 amp.

The type 5702 subminiature tubes used will operate to 265°C, endure shocks to 450 g, centrifuging to 1000 g, and vibration at 2.5 g (96-hr fatigue test). A DOFL test of ten 5702 tubes for 25 hr at 20 g rms produced no failures (ref 3, 4). The minimum operating filament voltage was 5.7 v; the maximum, 6.9 v. The maximum screen voltage is 155 v, with that for the plate, 200 v. The heater-to-cathode voltage range is from -200 v to +200 v. The transconductance range is from a minimum of 4200 μmhos to a maximum of 5800 μmhos.

Appendix B -- EQUIPMENT USED IN AMPLIFIER TESTING

The environmental chamber (fig. B1) at DOFL has inside dimensions 5 x 5 x 5 ft. It is equipped to maintain temperatures under sea level conditions from -100°F to 220°F. An electrodynamic vibrator is attached with a force output up to 3500 lb over a frequency range from 5 to 2000 cps. While the chamber has humidity controls, during the first series of tests discussed in this report, humidity was not recorded and there were no additions to the initial moisture content of chamber air. Humidity to saturation was used during the high temperature hour in four tests of the second series.

The ambient temperature of the chamber was obtained from shielded thermocouples suspended near a test object. There is also a thermocouple record of the temperature of air entering and leaving the chamber. The accuracy of the recording and measuring equipment was more than adequate for the tests.

Electronic power supply and monitoring equipment are shown in figure B2.

The recording instruments (fig. B3) used in the controls of the environmental chamber are listed below with accuracy ratings supplied by manufacturers. Because the nature of the test permits substantial variations in the parameters, additional calibration of the recorders was not requested. The greatest percent of inaccuracy reported is in the magnitude of acceleration of the vibrator. This could be as much at 5 percent at 20 g rms, which is less than the observed variations in the recordings.

In the second series of tests the required low temperature was obtained by placing a hood over the amplifier and injecting a stream of carbon dioxide. This hood was also used to introduce humidity during the high temperature part of the test.

Instrumentation of Controls of Environmental Chamber

Dry Bulb Recorder-Controller (Control temperature)
(Accurate to ± 1°F)

Strip Chart Recorder (Thermocouple Temperatures)
(Accurate to ± 1°F)

Acceleration Recorder
(Accurate to ± 0.5 g)

Frequency Recorder
(Maximum error of 2% in readings)

Precision Aneroid Monometer
(Maximum error of 3% in readings)

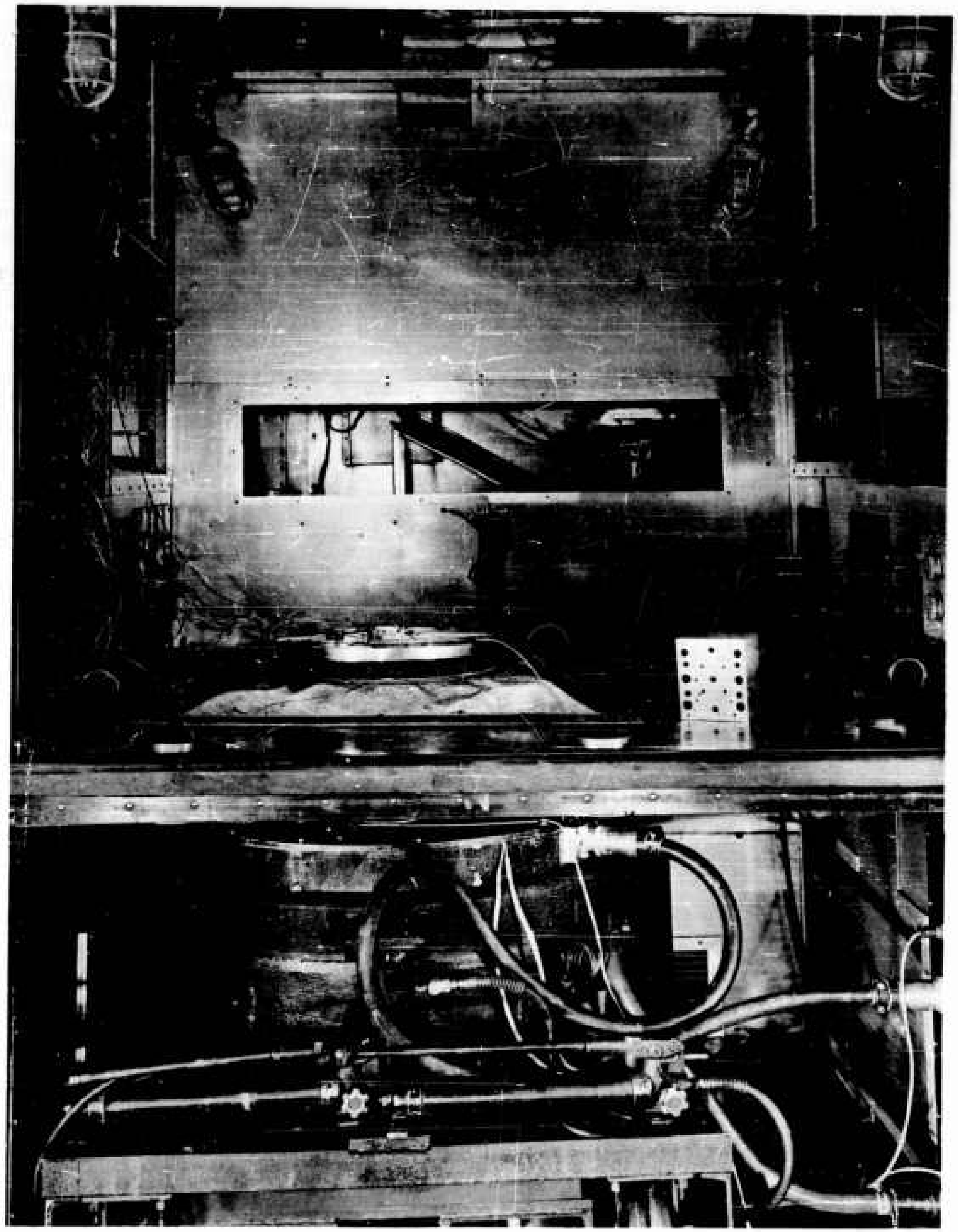

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Figure B 1. Interior of test chamber

(A) Upper section - showing test amplifier mounted on vibration exciter table

(B) Lower section - showing vibration exciter

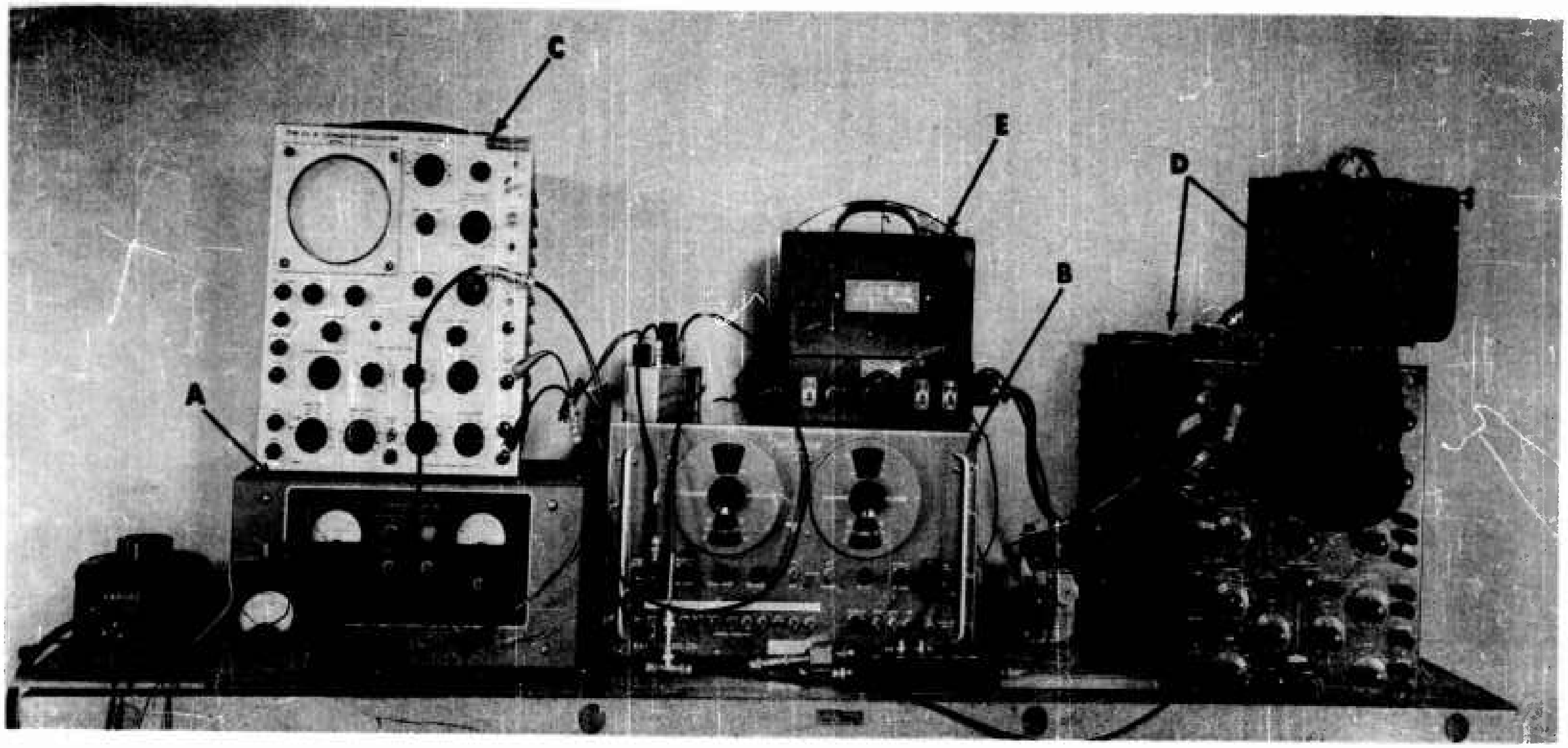

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Figure B 2. Electronic power supply and monitoring equipment

(A) Power supply for test amplifier
(B) Sweep generator
(C) Oscilloscope for monitoring amplifier output
(D) Oscilloscope and camera for recording amplifier output
(E) Camera control unit

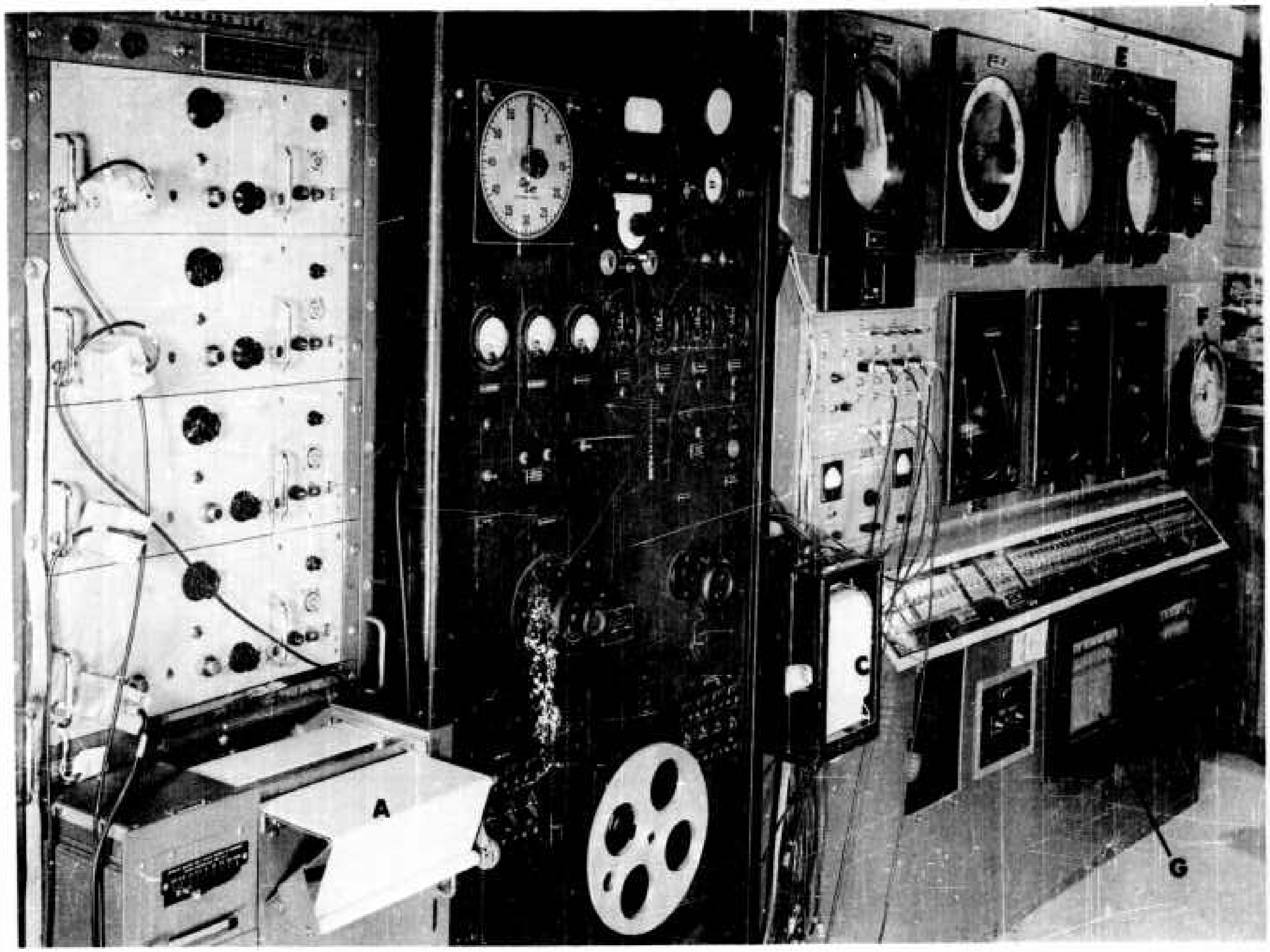

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Figure B 3. Control and recording equipment used in tests

(A) "G" level recorder
(B) Vibration exciter control console
(C) Frequency recorder
(D) Chamber temperature recorder-controller
(E) Altitude recorders
(F) Aneroid manometer
(G) Strip chart recorder for thermocouples

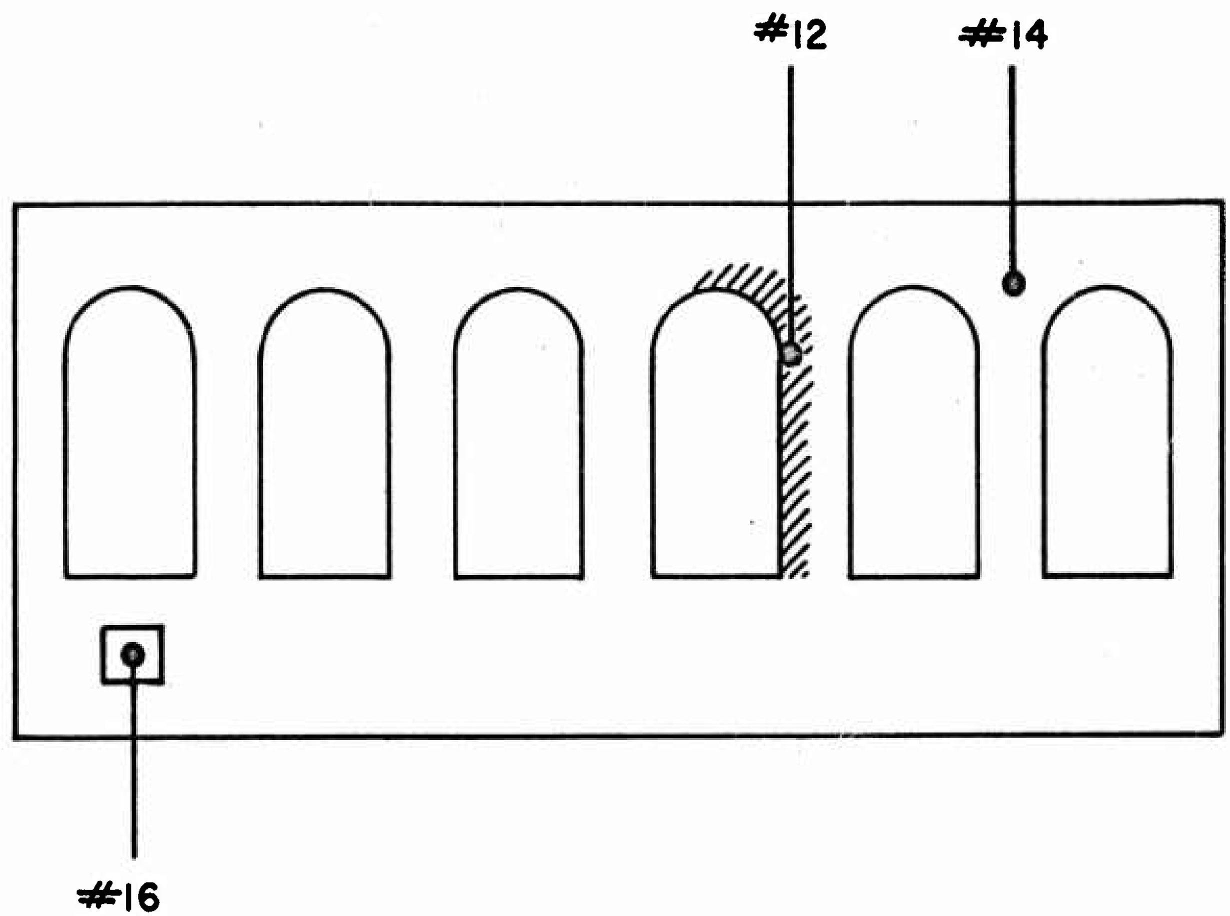

Figure B4. Mounting of thermocouples during testing of six-stage amplifier No. 2.

Figure B4 shows the mounting of thermocouples used to record temperatures at different points within the six-stage amplifier. Thermocouple No. 12 was mounted between the tube envelope and the wire-mesh tube holder. Thermocouple No. 14 is embedded in the aluminum case. Thermocouple No. 16 is mounted on a capacitor. These thermocouples were mounted in this way for comparing the effects of temperature differences on representative components.

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Environmental testing—Mathematical techniques

Instrument reliability

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